Offshore Wind Accelerator

Recommended Practices for Floating LiDAR Systems

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Foreword

This document is the Offshore Wind Accelerator Recommended Practice for floating LiDAR systems. Floating LiDAR systems (FLS) have emerged as wind resource assessment tools for offshore wind farms, with the potential for greatly reduced installation costs compared to fixed met masts in some cases. The challenges that FLS face and have to overcome to be considered as effective wind measurement options can broadly be grouped in two categories:

- The movement of the sea imparting motion on the LiDAR, and the subsequent challenge of maintaining wind speed and direction accuracy;
- The remoteness of the deployed system necessitating robust, autonomous and reliable operation of measurement, power supply, data logging and communication systems.

There is no standard that describes how a FLS should be deployed to get the best quality data for a wind resource assessment. A recommended practice document is therefore required to guide the use of FLS as a data source in wind resource assessments that lead to predictions of annual energy production. This document directly uses and builds upon a previously issued collection of recommended practices, which was issued by IEA Wind[1], and should be considered as a further development of recommended practice with greater detail provided in many areas.

The goal of this document is to codify existing industry and academic best practices to help ensure that the best quality FLS data are made available for use in the wind energy resource assessment process.

This document has been developed by a group of FLS expert practitioners and reviewed by experienced industry stakeholders.

[1] IEA Wind Annex 32 Work Package 1.5, "State-of-the-Art Report: Recommended Practices for Floating LiDAR Systems". Issue 1.0, 2 February 2016.

http://www.ieawindtask32.ifb.uni-stuttgart.de/wp-content/uploads/2016/01/IEA-StateOfArtFloatingLIDAR-2Feb2016_v1.0.pdf

Important notice and disclaimer

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Nomenclature

Abbreviations

AIS	Automatic Identification System, a radio-based marine vessel identification system
CNR	Carrier-to-Noise Ratio
EV	Environmental Variable
FLS	Floating LiDAR system, or floating LiDAR systems
GPS	Global Positioning System
KPI	Key Performance Indicator
LiDAR	Light Detection and Ranging, also 'LIDAR'
Met mast	Meteorological mast, or tower
MS	Method Statement
OEM	Original Equipment Manufacturer (in this context of the FLS)
RACON	A radar transponder (from RADar and beaCON) used to mark maritime navigational hazards
REWS	Rotor-Equivalent Wind Speed
RSD	Remote Sensing Device, here meaning LiDAR and/or Sodar
Sodar	SOnic Detection and Ranging, or SOund Detection and Ranging, also 'SODAR'
WRA	Wind Resource Assessment

1 Introduction

Wind resource assessment is a maturing discipline, important to investment decisions in wind farm development, which uses a range of information sources. Traditionally, for both onshore and offshore wind farms, sensors mounted on meteorological masts ("met masts") have been regarded as the preferred information source, and often used to characterise local wind regimes in advance of constructing large wind farms.

At the time of writing (2015/16), there is no formal wind resource assessment standard. Instead, processes for measuring the wind speed and direction and subsequent performance of a wind turbine at that site are largely based on the International Electrotechnical Commission (IEC) 61400 family of standards [2,3]. These standards require that wind speed measurements be made using calibrated mechanical cup anemometers that have a documented response to changes in environmental conditions. The standards also require that wind direction measurements be made using wind vanes. The use and deployment of cup anemometers and vanes is backed up by calibrations (e.g. MEASNET [4]), an extensive and well-developed body of knowledge about how they perform under different environmental conditions, well-established standards for use, and an experienced user-community.

Non-traditional remote sensing measurement devices are being increasingly used in wind resource assessment. The two types of device in most common use are LiDAR (also 'LIDAR', from LIght Detection And Ranging) and sodar (also 'SODAR', from SOnic Detection And Ranging, or SOund Detection And Ranging). They can characterize the wind resource at multiple heights from near ground to above typical wind turbine hub heights. The deployment of remote sensing may provide wind project developers with useful information that can be used to reduce the costs associated with wind data collection at heights greater than can be achieved using traditional monitoring towers. The use of remote sensing as part of a well-planned and properly implemented wind resource measurement campaign involving a diverse suite of measurement techniques may also contribute to the overall reduction of uncertainty in a formal wind energy production assessment. Unsurprisingly, as there is no general formal wind resource assessment standard, there is no formal standard for the use of LiDAR and sodar in that context either. However, an IEA Wind recommended practice [5] has been developed which represents a significant milestone on the route towards a standard for this technology.

1.1 The need for a recommended practice

Floating LiDAR systems (FLS) have emerged as wind resource assessment tools for offshore wind farms, with the potential for greatly reduced installation costs and timescales compared to fixed met masts in many cases. The technology is not yet fully mature and there are a number of systems and concepts; at the time of writing (2015/2016) a number of systems have been deployed on "real" wind resource assessments, a greater number have recently undergone, are currently undergoing, or are planned to undergo sea trials, and still further systems are under development. Despite all these activities, compared to the use of cups and vanes for wind resource assessment, or even compared to the use of LiDARs for onshore projects, the level of usage and associated expertise is currently still small. The challenges that FLS face and have to overcome to be considered as effective wind measurement options can broadly be grouped in two categories:

- The movement of the sea imparting motion on the LiDAR, and the subsequent challenge of maintaining wind speed and direction accuracy;
- The remoteness of the deployed system necessitating robust, autonomous and reliable operation of measurement, power supply, data logging and communication systems.

There is no standard that describes how a FLS should be deployed to get the best quality data for a wind resource assessment. A recommended practice document is therefore required to guide the use of FLS as a data source in wind resource assessments that lead to predictions of annual energy production. This document directly uses and builds upon a previously issued collection of recommended practices, which was issued by IEA Wind [1], and should be considered as a further development of recommended practice with greater detail provided in many areas.

This document is described as recommended practice rather than best practice for two reasons. Firstly, the track record of FLS deployments is relatively short, so the evidence base for asserting “best” as opposed to “currently recommended” practice does not exist yet. Second, this document is more authoritative and comprehensive in some areas than in others, so is not thought to be complete enough (yet) to qualify as best practice. This last point is expanded on in Section 1.6.

1.2 Document Goal

The goal of this document is to combine and codify existing industry and academic good practices, and elements of related standards and guidelines, to help ensure that the best quality FLS data are made available for use in the wind energy resource assessment process. This includes practices to reduce the uncertainty of data and practices promoting high data availability during a measurement campaign.

1.3 Calibration, Verification and Validation

It is useful to introduce some definitions of commonly used words for which meaning often overlaps in common usage:

- **Calibration**: operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication
- **Verification**: provision of objective evidence that a given item fulfils specified requirements
- **Validation**: verification, where the specified requirements are adequate for an intended use.

These definitions come from the International Vocabulary of Metrology [6]. To provide some context, in the IEA Wind recommended practice for the use of remote sensing devices [5], **verification** is widely used for the act of comparing Remote Sensing Device (RSD) measurements against those from cup anemometers, and **calibration** is used for example as the act of relating a cup anemometer's rotational speed to a measurement standard wind speed in a wind tunnel. As such these uses are consistent with the above definitions. It is noted also that although the use of the word **validation** is absent from [5], **verification** is always carried out with the purpose of **validating** the device for a specific use, therefore the terms are very similar in meaning in this context.

For the current purpose concerning FLS, we will prefer the term **verification** as the act of obtaining confidence in a system's measurement accuracy, by comparing with measurement results from other systems with established accuracy, which will be, or will be derived from, a **calibrated** measurement device.

1.4 Applicability

This document is designed to guide the use of LiDARs mounted on floating platforms for the resource assessment phase of an offshore wind farm development, or for trials of such systems intended for that application. In this context, the LiDAR is assumed to be of the types currently in most common use for this purpose, i.e. of fixed scan geometry and vertically-profiling. As well as a location to site the LiDAR, the floating platform is assumed to house or mount associated systems suitable for autonomous operation, namely power and communication systems. The floating platform itself is assumed to consist of a tethered buoy, which is inclusive of both quasi-static ("spar buoy") and more standard marine buoys which float on the surface and move substantially with waves (here called a "marine buoy"), as well as any other buoy. Figure 1 provides a schematic figure of some typical buoys.

The LiDAR types assumed here are consistent with the LiDAR types considered in the Remote Sensing Device (RSD) recommended practice [5], namely LiDARs which measure a vertical profile, and excludes those measuring in a horizontal manner. Furthermore, in this document it is assumed that the FLS supplier provides mean wind speed and direction data for a specific height over a period of time, which is assumed to be a 10 minute period. The derivation of time-averaged quantities from instantaneous quantities by the end user is not recommended. To relate this document to that for RSD recommended practice [5], here the focus is on using Time-averaged wind vector data (section 5.1.3 of [5]) rather than Instantaneous wind vector data (section 5.1.2 of [5]).

Use of FLS for other purposes (for example wake effects or power curve studies) is not directly addressed by this document, however some of the practices presented here may be helpful in guiding such deployments.

As stated above, guiding the use of FLS for wind resource assessment (or trialling of a FLS with that purpose in mind) is the overall purpose of this document. In so doing, all of this document will be of interest to the Original Equipment Manufacturers (OEMs) of FLS. In particular, new entrants to the OEM market will find configuration advice on the make-up of a FLS in Section 2, and OEMs at the point of supplying their systems or services will find advice on how to characterise their FLS in Section 3.

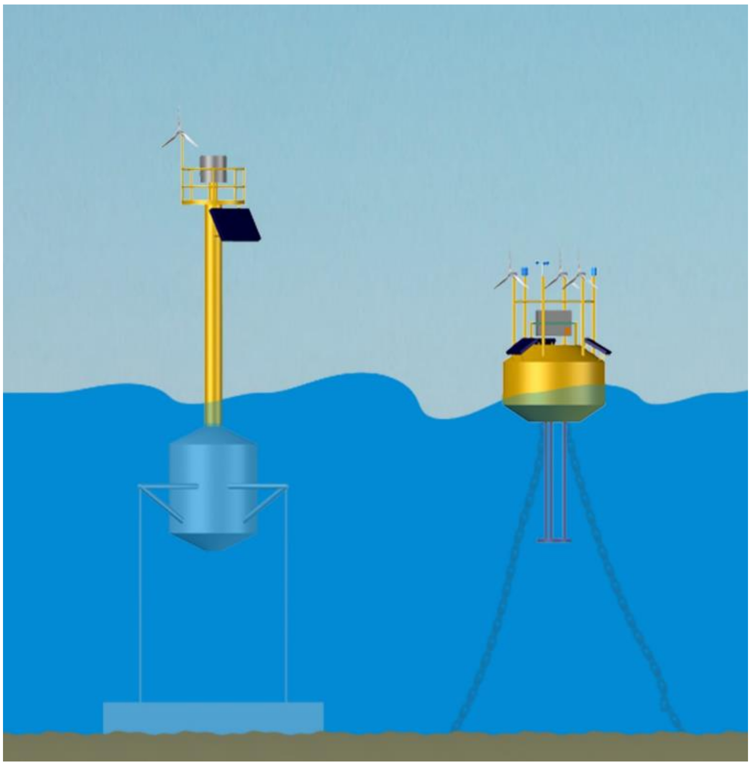

Figure 1: Quasi static spar buoy (left) and more standard marine buoy (right).
Note that other buoy designs are possible.

1.5 Limitations

The recommended practices in this document are intended to complement training and documentation provided by FLS manufacturers or suppliers. This document has been written assuming that the reader is familiar with the basic process of wind resource assessment and typical wind instrumentation, and is not intended to be a 'how-to' guide for the process of wind resource assessment. This document does not provide information on when to use a FLS in preference to or in combination with other measurement systems.

Use of FLS for the measurement of wind speed and direction is within scope; as their use for other purposes including measurement of turbulence and gusts is at a far lower level of maturity this is not within scope. (However, some related notes and advice do appear in this document as it is prudent to manage such measurements well, even if we have to wait for understanding to develop on how to confidently exploit the data.)

The recommended practices are not provided as a complete set of all practices to be adopted to ensure a successful wind measurement campaign using FLS; rather, they are a collection of individual recommended practices which have emerged from the expert and user community whose adoption will benefit the industry as a whole and provide a useful benchmark.

Most importantly, in areas where there are safety implications, for example (but not limited to) system deployment and mooring, observations and recommendations are made here from the wind resource assessment point of view, and these are not commensurate to safety guidelines.

1.6 Using this document

This document is structured such that the subject matter is presented in an order notionally consistent with a project timeline for a FLS deployment. This order and the main section headings are summarised in Figure 2. An overview of each of these sections is described below:

- **Configuration.** There is sufficient industry experience to inform requirements on the make-up of the FLS, for example which components should be present and what their specifications should be; these are detailed in this section.
- **Characterisation.** There are a number of different FLS models available from different suppliers, and each model has its own characteristics. These characteristics should be detailed by the FLS OEM so that the procurer of an FLS or of FLS services has a good understanding of what they are procuring. Also, in the event of problems arising during deployment there is a desire to understand the issues and determine a remedial plan of action, and experience has shown that having a written system description at an appropriate level of detail can be of real benefit. This section details the information which should be supplied by the OEM in order to characterise the system to an adequate level. This characterisation is in broad terms a detailing of the elements of the Configuration section, and the data provided is an important part of Assessment of Suitability.
- **Assessment of Suitability.** This section describes recommended practices for determining whether a candidate FLS is suitable for deployment in an offshore FLS trial or for WRA purposes. This consists of evaluating the information provided by the OEM (Characterisation), and refers to the OWA Roadmap [7].
- **Trial Campaign Design.** This section describes recommended campaign parameters for the case where the purpose of the deployment is to trial a FLS, and refers to the OWA Roadmap [7]. Specification for recommended reference measurement systems is included in this section. (Note that the use of a LiDAR as a trusted reference source is allowable.)
- **Wind Resource Assessment Campaign Design.** This section describes recommended campaign parameters for the case where the purpose of the deployment is to support wind resource assessment.
- **Trials Results Assessment.** If the purpose of the deployment is to trial a FLS, the question arises as to how to best assess the results of that trial. This section describes the required

data processing and comparisons and also relevant compliance and acceptance thresholds. This section also refers to the OWA Roadmap [7].

- **Wind Resource Assessment.** Recommended practice in processing and accepting the measured data in support of wind resource assessment is described here.

- **Planning and Permitting.** This section sits outside the main flow of the document, and collects experiences in obtaining the necessary planning consent, permits and/or licenses for the deployment of a FLS.

As indicated on Figure 2, three different reader objectives, and routes to those objectives, are considered:

- Planning and performing a FLS Trial – Red Route.

- Planning and performing a wind resource assessment campaign using a FLS, where trialling the FLS has not yet been performed and is part of the planned campaign – Green Route.

- Planning and performing a wind resource assessment campaign using a FLS, where a FLS trial has already been successfully performed – Blue Route.

It is recognised that this collection is more comprehensive and therefore authoritative in certain sections than in others. Items relating to installation, licensing, and safety are in particular advisory in nature and fall well short of being comprehensive. For this reason these topics feature in the **Recommendations for Future Work** section, along with a collection of other points.

This document highlights two different results in the text with an underlined, bold label and number. For example:

- **Note 1.** These points are for information only and may explain or expand on a recommended practice. They may also highlight where more research or development is required.

- **RP 1.** These points are the specific recommended practices that should be followed.

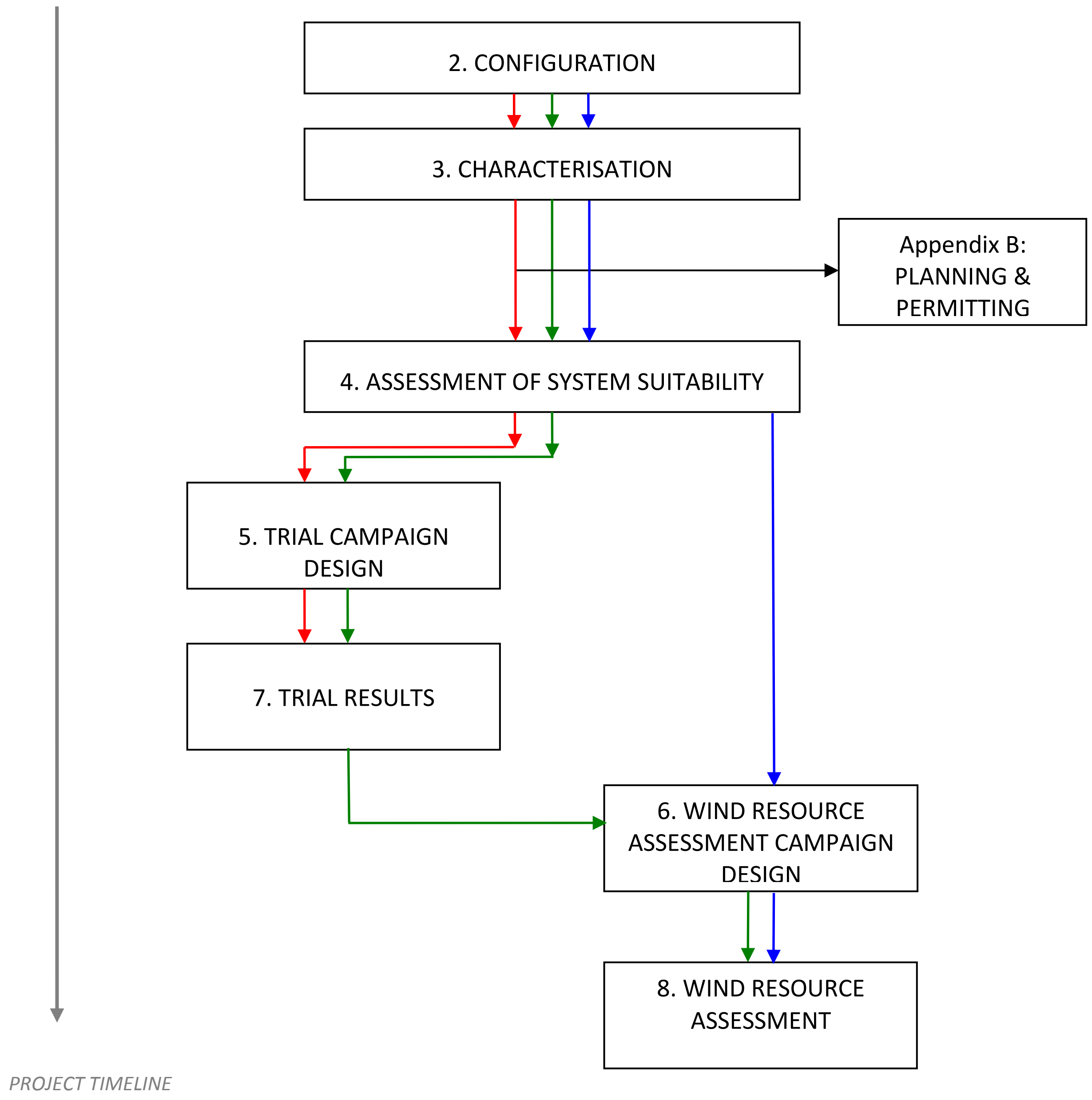

Figure 2: Layout of this document and notional project timeline. Red, Blue and Green routes are described in Section 1.6.

1.7 Authors

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- Detlef Stein (DNV GL)
- Hans Verhoef (Energy research Centre of the Netherlands (ECN))
- Ines Würth (University of Stuttgart)

The authors of the current document are also indebted to the authors of the fore-running IEA Wind document on RSD recommended practice [5], which can be seen as the starting point for the present work and from which much of the layout and style and indeed some of the introductory material has been borrowed. This recommended practice builds on information that is publicly available, including results from floating LiDAR trials reported in peer-reviewed journal and conference papers [8,9,10,11] and the Offshore Wind Accelerator commercialisation roadmap [7]. All sources are cited in the text and a complete list of references is given in the Bibliography (Section 10). The reader is recommended to consult documentation provided by the FLS suppliers in addition to these materials.

1.8 Reviewers

This document has been reviewed by subject matter experts in national laboratories, academia, and the wind energy industry. These reviewers are identified (in no particular order) in Table 1. All comments and contributions were helpful and appreciated. Reviewers who were involved in the fore-running document (see [1]) are noted, as well as reviewers for the current document.

Country	Organisation	Name
Belgium	AXYS Technologies NV	Matthias Borremans
Canada	AXYS Technologies Inc	Graham Howe, Breanne Gellatly
Denmark	DONG Energy	Nicolai Gayle Nygaard, Niall Connell, Miriam Marchante Jimémez
France	Leosphere	Matthieu Boquet, David Langohr
Germany	DEWI	Beatriz Canadillas
Japan	Mitsubishi Electric	Shumpei Kameyama
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Spain	Iberdrola	Javier Rodriguez Ruiz
Spain	EOLOS	Rajai Aghabi
Spain	IREC	Miguel Angel Gutierrez
UK	RWE	John Slater
UK	SSE	Adrian How
UK	Zephir	Mark Pitter
UK	SeaRoc	Jane Haviland
UK	Babcock Marine & Technology	Andy Paterson
USA	NREL	Andy Clifton

Table 1: List of reviewers.

2 Configuration

There is sufficient industry experience to inform requirements on the make-up of the FLS, for example which components should be present and what their specifications should be; these are detailed in this section.

This section is closely related to Section 3 and Section 4, where characterisation and suitability assessment recommended practices are described.

2.1 Using this Section

For those planning to use a FLS for wind resource assessment, or planning to trial a FLS for that purpose, this section is useful for:

- Providing a general background on the recommended make-up of FLS systems;
- Providing a means to perform an initial assessment of the suitability of a candidate FLS system.

This section should also be useful for FLS OEMs or potential FLS OEMs, particularly those considering entering the supplier market, as it provides a general perspective on the requirements of the system make-up.

Note that the related topic of the information which the FLS supplier should provide is described in Section 3. Also, recommendations on how to make a detailed assessment of FLS capability is described in Section 4.

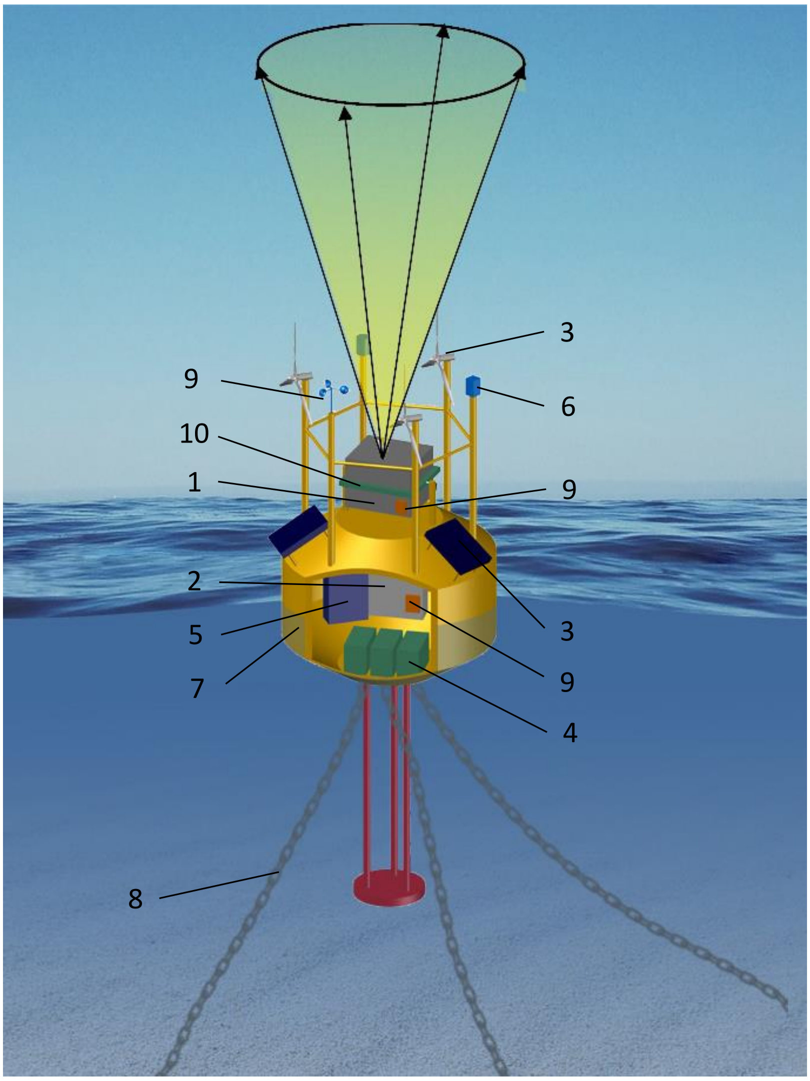
2.2 Overall Configuration

<u>RP 1: Essential Components.</u>

The FLS should consist of the following essential components:

- LiDAR;
- FLS operating system;
- Power system;
- Data logging and communication;
- Floating platform;
- Safety system;
- Station-keeping system.

The supplier of the FLS should supply all components as an integrated system; integration of individual components by the owner / customer is not recommended. All components should be suitable for use in a marine environment and have certification and/or warranties that meet the planned campaign duration. A schematic drawing of a FLS and its components is given in Figure 3.



1 Lidar

2 FLS operating system

3 Energy generation system

4 Energy storage system

5 Data logging system

6 Communication system

7 Floating platform

8 Station-keeping system

9 Sensors

10 Motion compensation

Figure 3: Schematic drawing of a FLS and its components.
Note other buoy designs and mooring systems are possible.

RP 2: Wave Sensors.

The FLS should also feature wave sensors, or alternatively be deployed in conjunction with separate wave sensors. (The specific metocean characteristics which should be available are those specified in Section 5.4.)

RP 3: Modular Construction.

It is advisable to modularise the construction to allow offshore replacement (assuming suitable conditions) rather than full recovery of the FLS. This applies to the LiDAR unit, batteries, renewable power generation units, communication components and data logger as a minimum.

RP 4: System Redundancy.

It is advisable to consider system redundancy in the overall scheme design, for example in the power generation and storage system, data storage and communications systems.

2.3 LiDAR System

Note 1: General standard of LiDAR.

The capability of the type of LiDAR unit being employed should meet current industry expectations in onshore and/or offshore fixed platform configurations. A batch-produced model which has demonstrated its suitability for use in a marine environment will inevitably be considered less risky, in terms of reliability, than a one-off prototype system.

RP 5: Model of LiDAR is accepted in the industry.

The model of LiDAR on the FLS should have a history of successful use in wind resource assessments. Mass-produced systems that have a stable engineering design are recommended over prototype systems.

Note 2: Presence of motion compensation.

The FLS may or may not include motion compensation systems. In either case evidence should be provided which justifies the design (see Sections 4.2 and 4.3).

2.4 Power System

RP 6: Power sources.

All FLS should include an intelligent power system that prioritizes safe operation of the FLS. For example, navigation lights should have priority over other systems in low-energy situations.

Note 3: Considerations for power sources.

The power requirements of the FLS could be met by a number of power sources. The most commonly used power sources are a combination of renewable (solar and wind) devices used in conjunction with rechargeable batteries and/or fuel cells. Liquid-fuelled generators are also used in some systems.

Performance of on-board wind turbines can be less than anticipated, probably due to aerodynamic interference from the structure itself.

Wind turbine blades are susceptible to damage from water impact during storms.

Independent solar-powered navigation lights are available as primary or backup lights. These can provide some redundancy in the FLS lighting in the event of catastrophic power system failure.

Solar panels may be susceptible to impact damage if not adequately protected for the installation and storage methods chosen.

Bird fouling and marine growth (e.g. algae) has been known to seriously degrade solar panel performance. The circumstances in which this can happen, and design measures to prevent or mitigate this effect, do not appear to be well understood in the industry.

Bird spikes can be effective in prevention of bird fouling.

An under-estimation of power requirements, and over-estimation of renewable power source effectiveness, have been known to cause availability problems.

The relative motion between the floating platform and a stabilised LiDAR device can cause wear and damage to cables.

Note 4: Design of the energy generation and storage system.

There are multiple approaches to ensuring that adequate power is available to the FLS at all times. Different combinations of generation and storage capacity, redundancy, and robustness may all result in a satisfactory system. The ease or difficulty of swapping out components, and distance from port, may also be factors. For these reasons no specific combination is recommended.

The primary objective of the power system is to provide adequate power for the entire campaign to ensure no interruptions in system and data availability. This is why it is essential that the FLS provides multiple power supply sources. In the event of damage or loss of one of the power supply sources there should be an independent back up power system that keeps the FLS functioning until the damage can be repaired, which can sometimes be several weeks or months depending on weather conditions and season at the specific measurement site.

RP 7: Design for battery replacement.

All systems should be designed with ease of battery replacement considered. Cabinets should be easily accessible for opening/closing and re-sealing. The seals should be tested onshore as a seal failure short circuits the batteries. Opening and closing of the seals should not affect the functionality of the seals offshore.

2.5 Data Logging and Communication

RP 8: Data logging system.

The data logging system should have on-board storage capacity sufficient for the planned duration of the deployment, with an extra 3 months of storage for contingency. Ideally the FLS should provide data redundancy capacity where the primary data storage device can be backed up to a secondary storage device (to avoid data loss should the primary data storage device become damaged or corrupted).

RP 9: Communications system – real time.

The communications system should enable data transfer to shore in real time, or close to real time. If power or bandwidth is limited, a subset of diagnostic data that includes system performance and health should be defined and take precedence over other data.

RP 10: Communications system – redundancy.

The communications system should have more than one channel of communication (e.g. cell phone network protocols, satellite communications, radio). Switching between channels of communication should be automatic or under remote control.

RP 11: Communications system – wireless.

The communications system should include a wireless communication channel suitable for use from a nearby work boat.

2.6 Ancillary Measurement Equipment

RP 12: Wave sensors.

It is essential that, while the LiDAR unit is recording wind speed and direction, the sea state is also simultaneously measured, and those sea state data are recorded. This could be achieved through sensors mounted on the floating platform, or through other sensors deployed separately in the vicinity. Wave sensors should be designed for marine conditions. Wave sensors should have a history of successful use in meteorological and oceanographic applications. Mass-produced systems that have a stable engineering design are recommended over prototype systems. (Details of the metocean measurements required are included in Section 5.4.)

RP 13: Secondary wind speed and direction sensors.

It is essential that, while the LiDAR unit is recording wind speed and direction, secondary sensors are recording the same quantities for use as a cross-check to verify operation. Cup anemometers and wind vanes or sonic anemometers deployed 1 to 3 m above platform level are sufficient for this application.

Note 5: Other data sensors.

In addition to the LiDAR and wave sensors, it is recommended to have additional sensors on the FLS to provide additional wind resource data, to understand the LiDAR performance, and to provide a broader dataset to support future data analysis. Examples of additional data that may be required include:

- Air temperature;
- Humidity;
- Air pressure;
- Vertical air temperature profiling – acknowledging that this is currently difficult to achieve;
- Buoy motion;
- Video (e.g. to monitor bird fouling, or remote from the FLS to monitor overall status).

With respect to FLS trials, where FLS wind measurements are compared with those from reference systems, specification for recommended reference measurement systems is included in Section 5.

2.7 Floating Platform

RP 14: Safe access to the FLS for personnel.

In the case where maintenance access onto the buoy for personnel is required, the floating platform should have provision for safe boarding, including access points and space for at least two people to board the platform and access all systems. Safety features such as handrails, attachment points, and fenders should be part of the design.

It must be possible to verify before boarding that the FLS buoy is de-energized. This reduces the risk of electric shock due to shorts to the buoy hull and other faults.

RP 15: Access from work boats.

The floating platform should be accessible from a variety of work boat sizes and types (which should be specified by the supplier, see Section 3.7).

Note 6 : Emergency assistance for injured personnel

It is noted that should a person become unconscious, or unable to disembark the FLS unaided, it may be required to have 3 people on the FLS (the injured party and 2 others acting as rescuers). The design assessment should take this into account. Consideration should also be given to rescue of casualties and transfer back to a work boat of stretcher bound and/or unconscious casualties.

Note 7: Risks of damage to the FLS.

FLS systems have been damaged by sea mammals and subject to vandalism. The risk of damage due to these causes is very dependent on location. The design should be resistant to tampering and damage, and utilize tamperproof screws, locked hull compartments and dry boxes, and underwater or out-of-reach sensor mounts.

RP 16: Navigation aids.

All buoys should have aids to navigation that conform to local requirements. These may be specified by the Coastguard or local equivalent. Also consider use of radio or radar-based identification systems such as AIS and RACON.

RP 17: Watch circle monitoring.

The FLS should monitor its location within a specified watch circle using GPS or equivalent. If the FLS moves outside this watch circle, an emergency notification should be sent to shore via communication channels. This message should include the location of the buoy. This information is required to warn shipping and aid in recovery.

2.8 Station Keeping

Note 8: Station keeping considerations.

Station keeping can be achieved through active or passive means. Active station keeping can be achieved through dynamic positioning using motors. However, passive station keeping is obviously more common, and typically takes the form of a mooring (anchor plus mooring line). Buoy motion in either case is restricted to an area known as the watch circle. In general the watch circle size may be reduced by using more than one mooring (e.g. a two point mooring) which also adds redundancy. Multipoint moorings are limited to shallower water, are more complicated to deploy/recover (including precise placement of the anchors) and usually twice as expensive as single point moorings. The benefit of this mooring is the reduced watch circle of the buoy and relatively fixed orientation of the hull if this aspect is important.

However, if all things considered allow for a single point mooring, this will make for the least complicated deployment and recovery logistics from minimizing the vessel requirements (no dynamic positioning required for station keeping; simpler deployment procedures), reduced time to deploy and recover and potentially expanded operational weather window (i.e. one does not need as calm conditions especially when the buoy is taken to its final position).

<u>Note 9: Risk of mooring failure.</u>

There are known instances of mooring or tethering failure, with resulting loss or significant damage to the FLS, notwithstanding risk to shipping. Such failures are seen as a major risk factor for FLS deployment.

<u>RP 18: Design of mooring system.</u>

This RP applies only to station-keeping systems of the mooring type. Mooring designs are site specific. A mooring design is not necessarily transferable from one site to another.

As moorings need to be designed according to local conditions and regulations by qualified experts – e.g. ocean engineers or naval architects usually provided or sub-contracted by the FLS OEM – the following design input parameters need to be provided to the experts:

- General Statements
    - All conditions, where applicable, may be 1-, 5-, 10-, or 25-year conditions; as dictated by data availability and project requirements. Seasonal data may be used for mooring design intended for short term deployments.
    - Typically, 50- or 100-year data is a requirement for structural design and may be used for mooring design, if available.
    - Data must be identified as measured (i.e. – monitoring stations) or modelled (i.e. – extrapolated or simulated). It is beneficial to include references to who performed the modelling and to reference the source of the base data set.
    - The less data available for mooring design, the greater the uncertainty of design. Where data is unavailable, justification of input design values must be given.
- Parameters for Design
    - Location (Latitude/Longitude)
    - Depth
        - Maximum Depth [Chart Depth + Highest Astronomical Tide (HAT) + Maximum Surge Height]
        - Minimum Depth [Lowest Astronomical Tide (LAT) or Chart Depth]
    - Significant Wave Height [Hsig]
    - Peak Period [Tp]

- Maximum Wave Height [Hmax]
- Ocean Current Profile
  - Surface currents required, water column profile is preferred if available.
- Site Bathymetry
  - Bathymetric survey charts if available, or reference best scale hydrographic chart of the region.
- Navigation Restrictions
  - Water Circle Restrictions, Unexploded Ordnance (UXO) Risk, or similar.

A third-party review of the mooring design is recommended.

RP 19: Use of suitable mooring components and material.

Only use components of suitable quality (e.g. corrosion-free) from reputable suppliers with shackle and chain manufacturer certification documents included. In particular, use components of compatible and consistent material, in order to prevent corrosion e.g. between different grades of steel for adjacent mooring parts like shackles, rings, swivels, chains etc. Should components of different steel grades be next to each other, isolation hardware (i.e. – phenolic block, isolation block, synthetic rope section) should be used to separate the dissimilar components to avoid galvanic corrosion. All connecting hardware must have stamped rated load limits.

RP 20: Applicable standards and guidelines for the design of mooring system.

In Table 2 a number of most frequently used standards and guidelines for mooring design are listed.

2.9 Transportation of FLS to site

RP 21: Transportation of the FLS.

It is recommended to transport the FLS from the quayside to the deployment site complete and commissioned to reduce on-site/offshore cost, time and complexity.

RP 22: Towing bridle.

If the FLS is to be towed, reducing the length of towing bridle where possible and minimising opportunities for snagging are desirable to prevent mishaps in deployment and retrieval.

Guidelines and Standards	Year of Publication
ABS	
Publication 39 Certification of Offshore Mooring Chain	2014
Publication 90 Application of Fiber Rope for Offshore Mooring	2014
Publication 194 Thruster-Assisted Mooring (TAM, TAM (Manual)) for Mobile Mooring Systems	2014
Publication 205 Pre-Laid Position Mooring Systems	2013
American Petroleum Institute	
API RP 2SK Recommended Practice for the Design and Analysis of Station-keeping Systems for Floating Structures	2008
API RP 2I In-Service Inspection of Mooring Hardware for Floating Structures, Ed.3	2008
API RP 2SM Design, Manufacture, Installation and Maintenance of Synthetic Fiber Ropes for Offshore Mooring,	2014
Bureau Veritas	
Classification of Mooring Systems for Permanent and Mobile Offshore Units	2015
DNV offshore service specifications, offshore standards and rules	
DNV-OS-E301 Position Mooring	2010
DNV-OS-E302 Offshore Mooring Chain	2009
DNV-OS-E303 Offshore Mooring Fibre Ropes	2013
DNV-OS-E304 Offshore Mooring Steel Wire Ropes	2009
IALA	
Design of Floating Aid to Navigation Moorings, ID 1066, Ed. 1.1	2010
INTERNATIONAL ASSOCIATION OF CLASSIFICATION SOCIETIES	
Requirements concerning Mooring, Anchoring and Towing	2014
NOAA	
NDBC Buoy Mooring Design Manual	2014
UK-HSE	
Research Report 219 Design and integrity management of mobile installation moorings	2004
Offshore Information Sheet No 4/2013 Offshore installation moorings	2013
HSE Safety Notice 3/2005 Floating Production Storage and Offloading (FPSO) - Mooring Inspection	2005
WMO	
GUIDE TO MOORED BUOYS AND OTHER OCEAN DATA ACQUISITION SYSTEMS by A. Meindl, DBCP Technical Document No. 8	1996

Table 2: List of applicable guidelines and standards for design of mooring systems

3 Characterisation

There are a number of different FLS models available from different suppliers, and each model has its own characteristics. These characteristics should be detailed by the FLS original equipment manufacturer (OEM) so that the procurer of an FLS or of FLS services has a good understanding of what they are procuring. Also, in the event of problems arising during deployment there is a desire to understand the issues and determine a remedial plan of action. Experience has shown that having a written system description at an appropriate level of detail can be of real benefit. This section details the information that should be supplied by the OEM in order to characterise the system to an adequate level, which is known as the FLS data pack. The Configuration section (Section 2) provides recommendations on how a FLS should be configured; this section provides recommendations on what information should be supplied to understand how a specific FLS system is configured; and the data provided is an important part of the Assessment of Suitability (Section 4) of the specific FLS system.

3.1 Using this Section

For those planning to use a FLS for wind resource assessment, or planning to trial a FLS for that purpose, this section is useful for:

- Assessing whether the detailed information supplied by the FLS service provider is sufficient to assess suitability;
- Ensuring that sufficient FLS information is gathered such that the procurer of FLS services is in an informed position should operational problems arise.

This section should also be useful for FLS OEMs, as it provides guidance on the nature of the system information which the FLS user will expect and/or require.

Note that the related topic of recommendations on how to make a detailed assessment of FLS capability is described in Section 4.

3.2 Overall Configuration

RP 23: Summary of system characteristics.

An overall description of the system should be delivered by the supplier. This data pack should include at least:

- The LiDAR manufacturer and model;
- Whether the buoy is of spar-buoy, marine buoy, or any other type;

- Whether motion compensation is employed: if so, what degrees of freedom are compensated, and whether this is applied in hardware and/or software;
- The metocean and/or other sensors included in the FLS;
- A signal/data flow chart comprehensively visualizing data acquisition and on-board data processing including motion compensation;
- The on-board power system;
- Systems for data storage and retrieval;
- The communication channels;
- A schematic diagram of the FLS.

RP 24: Supplier assessment of FLS maturity.

The supplier should specify the level of system maturity that is claimed for the overall FLS, according to the maturity categories defined in the OWA Roadmap [7] and summarised in Table 1A.

RP 25: Supplier evidence of FLS maturity.

The supplier should supply independently verified evidence to support their assessment of the FLS maturity level. This evidence should include information about wind speed and direction accuracy and system reliability.

RP 26: Provision of Dimensions and Weight Information.

The data pack provided by the FLS supplier should include detailed drawings and text that include:

- The overall dimensions of the FLS when out of the water;
- The submerged depth and protruding height (including ranges if applicable) of the deployed FLS;
- The overall weight of the FLS;
- Dimensions applicable to the approach of, and access of personnel from, maintenance vessels, e.g. touchpoints, overhangs, depths, and maximum and minimum heights of vessel fenders;
- The watch circle of the deployed FLS (insofar as this can be specified considering availability or lack of availability of detailed site information).

RP 27: Provision of operating/survivability conditions information.

The data pack provided by the FLS supplier should include:

- The design operating temperature range;
- The design operating ranges of metocean conditions (see Section 5.5). This should include breaking waves conditions;
- The design operating range of wind speed;
- The design operating range of water depth;
- Consequences, including data loss, data accuracy, and system integrity, if these ranges are exceeded.

The data pack should also include information on the range of conditions (beyond the operating range) in which the FLS is expected to survive, including any evidence from operational experience.

<u>RP 28: Provision of availability and maintenance information.</u>

The data pack provided by the FLS supplier should include:

- The nominal system availability when deployed;
- The nominal longevity of a deployment without maintenance visits;
- The offshore maintenance regime, including details of consumables and their replenishment schedule;
- The nominal longevity of a deployment before recovery and onshore maintenance is required;
- The service interval for the LiDAR system and whether this can be performed offshore or by returning onshore for factory conditions servicing. Also whether the LiDAR can be safely removed and/or replaced at sea or whether a harbour visit is recommended;
- Advice on proper storage conditions;
- Information on any required scheduled maintenance including maintenance schedule, even if the FLS is not being used.

<u>Note 10 : Competency Assessment of Maintenance Staff</u>

It should be noted that the offshore training requirements for FLS maintenance staff can vary and additional training may need to be scheduled to satisfy differing national/company requirements.

<u>RP 29: Provision of Method Statement (MS).</u>

The data pack provided by the FLS supplier should include a Method Statement (MS) for the deployment and recovery of the FLS. Where applicable, the MS should also include a description of how major components (LiDAR unit, batteries, renewable power generation units, communication components and data logger as a minimum) can be replaced *in situ* during an offshore deployment.

3.3 LiDAR System

RP 30: LiDAR characterisation.

The data pack provided by the FLS supplier should include a full description of the LiDAR employed, and the associated wind speed and direction measurement. This description should include:

- LiDAR-related characterisation, as detailed in RP1 of [5] and not reproduced here.
- A detailed description of how the wind direction (in a global reference frame) is to be determined, noting that the orientation of the LiDAR may vary.
- A description of how the wind speed is determined, namely whether it comes directly from the LiDAR as for a static deployment, or whether there are hardware and/or software motion compensation, and whether any software compensation is applied automatically or as a post-processing step. Note that "Motion Compensation" details are required, see below.
- If any other quantities are measured by the LiDAR, for example turbulence or gust speeds, these should also be specified, the manner in which they are determined explained, and any required post-processing specified.
- A detailed description of the data file that is provided to the users which records the measured data by the LiDAR. (Note that if the FLS uses any form of motion compensation, then the provided data file may differ from that provided by the LiDAR unit in isolation, but the same requirement to describe the data file applies).
- A detailed description of any applicable or variable filters on data quality, noting that these may be applied automatically by the system, may be applied as a post-processing step by the supplier, or may even be applied by the user as a post-processing step. A common such filter is for Carrier to Noise Ratio (CNR); for example the FLS supplier may detail which CNR threshold is applied automatically, or alternatively for example recommend an applicable CNR threshold and describe how a threshold can be applied to the data file.

RP 31: LiDAR type validation information.

The data pack provided by the FLS supplier should include evidence of the testing that the LiDAR has undergone at suitable test sites. This information may be used to substantiate the LiDAR maturity level and LiDAR performance claims.

RP 32: Information on use of the LiDAR type in the wind industry.

The supplier should report the extent to which the LiDAR has been used in WRA campaigns.

Note 11: Motion compensation and degrees of freedom.

The motion of the buoy can be described as six degrees of freedom (DOF) as shown in Figure 4. The six DOF include translation along and rotation about three axes: vertical axis, longitudinal axis and lateral axis. For translational motion, these are often referred to as heave, surge and sway respectively. Likewise for rotational motion, these are often referred to as yaw, roll and pitch respectively.

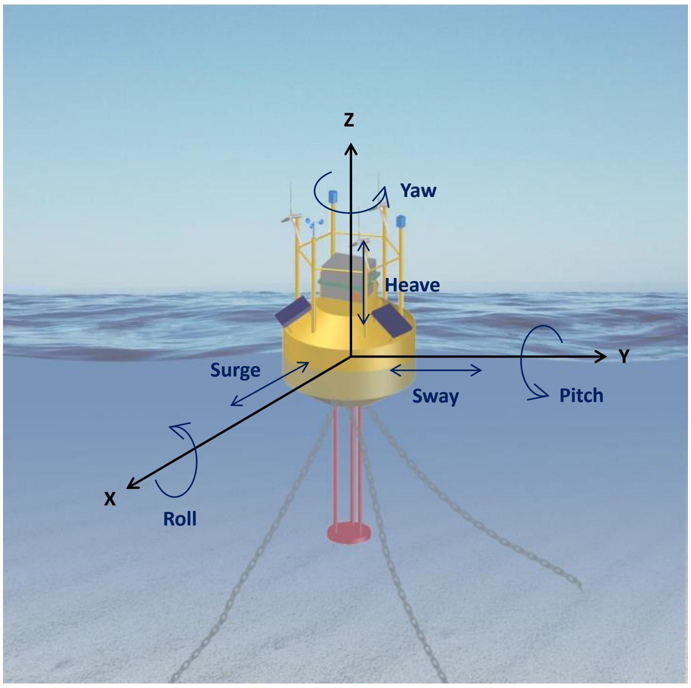


Figure 4: The six degrees of freedom of a FLS.

RP 33: Motion compensation characterisation.

The data pack provided by the FLS supplier should include a description of motion compensation systems and related design features, including:

- Maximum angle from the vertical from which the LiDAR's vertical axis will deviate during operation and the frequency of this occurrence.
- Maximum angular velocity that the LiDAR's vertical axis will experience in operation.
- Maximum horizontal and vertical components of velocity (in a global frame of reference) that the LiDAR will experience in operation.
- Specification of any motion compensation arrangements, which can consist of more than one of the following. An overview is given in Figure 5.

  - *Passive/Mechanical*. Unpowered, mechanical arrangements whereby the motion of the LiDAR due to the motion of the floating platform is reduced or negated. This could include gimbal or spring mounting, in which case the degree of travel permitted should be included.

  - *Active/Mechanical.* As for *Passive/Mechanical* but where the movement of the LiDAR is actively adjusted using powered actuation in response to sensed motions. The degree of travel permitted should be included.

  - *Active/Software.* In this case the motion of the LiDAR or the platform is sensed and the recorded wind speed and/or direction are corrected instantaneously and automatically by the on-board software.

  - *Active/Post-postprocessing.* In this case the motion of the LiDAR or platform is sensed, but the correction to the wind speed and/or direction is not applied automatically but as a post-processing step.

- For each of the six degrees of freedom, it should be stated whether motion compensation is applied.

- For all degrees of freedom for which there is motion compensation, the type of compensation used, and whether there are any limits outside which compensation is inoperative should be defined.

- In all cases where there is motion compensation using gimbals, if gimbal lock is avoided or mitigated.

- In all cases where the motion of the platform or LiDAR is sensed, the degrees of freedom which this applies to and the nature of the sensors used.

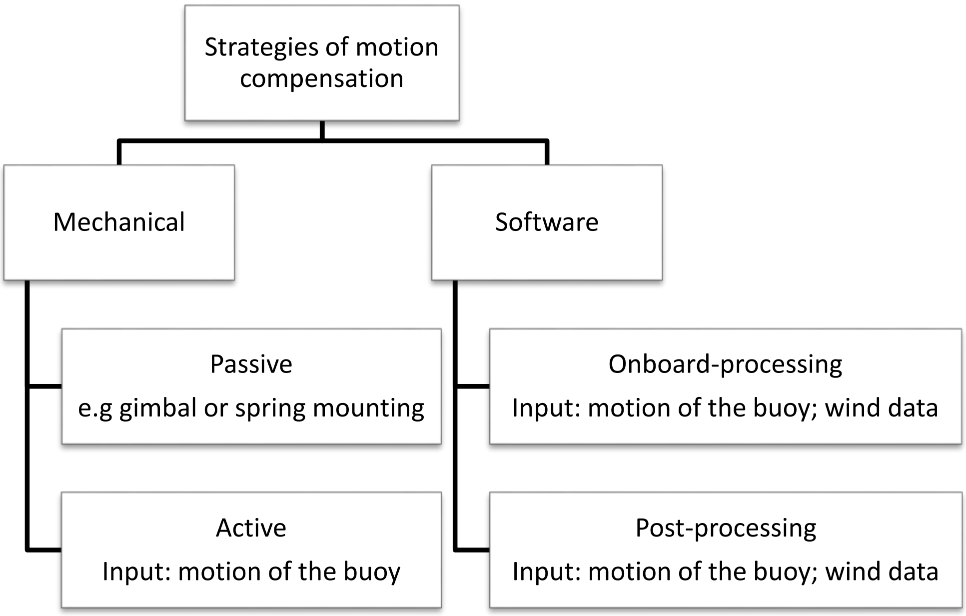


Figure 5: Overview of strategies for motion compensation; note that combinations are possible.

RP 34: MS for LiDAR set-up.

The MS should include procedures for set-up, test and verification of the LiDAR.

3.4 Power System

RP 35: Provision of power systems information.

The data pack provided by the FLS supplier should include:

- The power generation capabilities of the FLS. If renewable power sources are used, the generation conditions for which they are qualified.
- The power storage capacities of the FLS.
- For all power consuming items on-board, their power consumption, including but not limited to the LiDAR unit, any other sensors, the data logger, communication systems, the power systems themselves, and navigation aids.

3.5 Data logging and Communication

RP 36: Provision of data logging and communication information.

The data pack provided by the FLS supplier should include:

- List of sensors for which measurements are recorded.
- The rate at which data is logged and the quantities that are logged.
- Information with regards to on-board data processing, in particular when motion compensation and wind data statistics are deduced outside the actual LiDAR system e.g. by on-board/real-time processing (see RP 23).
- The on-board storage capacity for data. Information on planned data backups and redundancy of data storage.
- The communication systems, and protocols supported, and the rate at which data can be transferred to shore, including the expected data rate per day.
- Any aspects of the FLS control that can be managed remotely.

3.6 Ancillary measurement equipment

RP 37: Ancillary measurement equipment characterisation.

Besides the LiDAR, other atmospheric or metocean sensors may be present on the FLS, for example wave measurement, motion detection, or atmospheric temperature or humidity sensors. Any such sensor should be specified, the manner in which the data is gathered explained, and any required post-processing specified.

In the case where metocean sensors are to be deployed separate to the FLS, the sensor specification and placement requirements should be detailed.

RP 38: MS for ancillary measurement equipment set-up.

The MS should include procedures for set up, test and verification of all sensors and measurement equipment. For each sensor, it should be explicitly stated whether any in-situ calibration or check is required. For any such requirement, the method should be fully specified.

3.7 Floating Platform

RP 39: Maintenance access documentation.

Provision for safe access for maintenance personnel should be fully described in the supplied data pack. This should include advice on maximum wave height for safe access.

RP 40: Examples of suitable work boats.

The supplier should provide specific examples of work boats which are suitable to access the floating platform. The examples should also detail how access is to be made, e.g. if the bow or side of work boat is to be used. (Bow-on access as for offshore wind turbines is not generally suitable due to the inability of FLS to withstand boat thrust.)

RP 41: Assessment of damage risk.

A review of hazards and associated risk assessment should be carried out in respect of unwanted human or animal interference with the FLS. Mitigating actions (e.g. anti-boarding nets) should be put in place if deemed necessary. The hazard review, risk assessment and any mitigations should be made available by the supplier to the user.

RP 42: Specification of navigation lights.

Navigation lights should be fitted and steps taken to ensure their operation at all times. The specification of the navigation lighting system should be included in the data pack provided by the supplier.

RP 43: Specification of geo-location system.

A geo-location system should be fitted and steps taken to ensure their operation at all times. The specification of the geo-location system should be included in the data pack provided by the supplier.

3.8 Station-Keeping

RP 44: Provision of station-keeping design information.

A detailed schematic drawing of the station-keeping system, and of key dimensions and calculations associated with the design, should be made available by the supplier. The suitability of the system for the predicted wave, current and tidal conditions at the site should be demonstrated. For a specific arrangement, the limitations of its suitability for subsequent deployments to other sites should be detailed (for example deeper sites requiring longer tethers). Furthermore the drift radius or locus of the deployed FLS for the specific deployment should be provided.

RP 45: Experience with the station-keeping system.

Wherever possible, experience during prior deployments of using the station-keeping system should be detailed by the supplier. For example, if the planned deployment is the first for the system in question this should be clearly communicated. Also, any problems encountered with prior deployments should be detailed, and any remedial actions explained.

RP 46: MS for mooring.

In the case where a mooring system is used, the MS should include clear procedures, including:

- Method for installing moorings (if applicable);
- Method for securing the FLS to moorings;
- Method for inspecting moorings;
- Method for releasing from moorings;
- Method for removing moorings (if applicable);

The FLS deployment should have no lasting artefacts. Any sea-bed moorings should be fully removed. Local environmental regulations should be observed.

RP 47: MS for dynamic station-keeping system.

In the case where a dynamic station-keeping system is used, procedures should be detailed for the operation of the system for the entire deployment including installation, operation, and retrieval.

3.9 Transportation of FLS to site

RP 48: MS for transportation.

The MS should include:

- The recommended means for transport of the FLS to and from the quayside.
- The appropriate points on the FLS for securing during transportation.
- The recommended means for temporary storage of the FLS at the quayside.
- Method for any quayside assembly.
- Method for lifting from quayside to on-deck or in the water at the quay.
- Requirements on lifting machinery for uplift from quay.

- Sea conditions in which it is safe to transport FLS from quay to intended offshore location.
- For FLS systems which will be towed to site:
    - Requirements on vessel such that it is suitable for towing;
    - Safe towing speed and sea conditions envelope;
    - Description of safe procedure (e.g. avoidance of capsize and excessive snatch loads).
- For FLS systems which will be transported on deck:
    - Requirements on vessel such that it is suitable for on-deck transportation;
    - Safe transit speed;
    - Method for lifting from deck to deployment location;
    - Requirements on lifting machinery for same;
    - Sea conditions in which it is safe to perform uplift from deck.
- Any considerations for protection of equipment (e.g. LiDAR or power generating systems) during lifting activities.
- Procedure for positioning in intended location, including detailed method for confirming orientation of floating platform.
- For recovery of the FLS, a description of lifting and/or towing requirements and methods where they may differ from those for deployment.

4 Assessment of Suitability

Before a FLS has undertaken an offshore trial, it is reasonable to expect that the system was designed to operate reliably in the conditions likely to be encountered. FLS systems differ markedly in their conceptual design, nonetheless it is possible to determine some recommended practices in common.

This section describes recommended practices for determining whether a candidate FLS is suitable for deployment in an offshore FLS trial or for WRA purposes. This consists of evaluating the information provided by the OEM (see Section 3), and refers to the OWA Roadmap [7].

For a number of the recommended practices described in this section, a distinction is made between recommendations suitable for FLS trials and those for WRA purposes. In broad terms, for the purposes of a FLS trial, the system should have the potential to fulfil requirements, but has not necessarily demonstrated this ability; whereas for WRA purposes, the onus is on having substantially demonstrated capability in a previous trial.

4.1 Using this Section

For those planning to use a FLS for wind resource assessment, or planning to trial a FLS for that purpose, this section is useful for assessing the suitability of the candidate FLS for the intended purpose. Note that the recommended make-up of FLS systems is described in more general terms in Section 2, which allows for an initial assessment of suitability, however this section provides more details and is quantitative in nature where possible.

This section should also be useful for FLS OEMs, as it provides guidance on how the FLS user will assess the system capability.

Note that the information which is expected to be supplied by the FLS supplier, in order to enable the assessment described in this section, is described in Section 3.

4.2 Overall configuration

<u>Note 12: Accuracy and availability metrics with respect to FLS maturity claims</u>

The OWA Roadmap [7] introduced the concept of FLS maturity levels, which have been reproduced and summarised in Table 1A. These maturity levels are considered to be very useful indicators, and this document's recommended practices are consistent with the roadmap. To achieve "Pre-Commercial" maturity level, accuracy and availability acceptance criteria are proposed by the roadmap and are reproduced here (Table 2A and Table 3A).

In this document, the maturity levels are extended to relate acceptance criteria for the earlier ("Baseline") and later ("Commercial") maturity stages to the same accuracy and availability metrics: this is summarised in Table 4A, and further described in related sub-sections below.

Referring to Table 3A, in the Roadmap the Mean Wind Direction Offset is the intercept with the y-axis. In most circumstances this is applicable. However, in the case where the linear regression is less meaningful or may be misleading (for example if there is a wide wake-affected sector from which data is excluded) then it may be preferable to use the mean overall offset instead.

RP 49: Appropriate FLS maturity.

For the purposes of an offshore FLS trial, the claimed FLS maturity level should be at least "Baseline" according to the OWA Roadmap [7], (Table 1A). For the purposes of WRA, the claimed FLS maturity level should be at least "Pre-Commercial" according to the OWA Roadmap [7].

Note 13: Deploying a FLS at a lower maturity level

It is recognised that there may be a willingness to deploy a FLS where the maturity level is not recognised as being so far progressed; under these circumstances the owner/operator is accepting additional risk that the system does not perform as desired.

RP 50: Evidence of FLS maturity

The required level of maturity differs for the purposes of FLS trials and WRA deployments.

For the purpose of an offshore FLS trial, the evidence required consists of:

- Whether the LiDAR system itself is suitable (see Section 4.3);
- An assessment of whether the floating nature of the system has been adequately accounted for in the overall system design, in a manner which has the realistic potential to mitigate impacts (e.g. by waves, tides, currents, mooring, water depth) on wind speed and direction accuracy (see Section 4.3);
- An assessment of whether the overall system design is fit for purpose, in a manner which has the realistic potential to survive and operate in the intended environment, with specific advice provided below (see Sections 4.4 - 4.9);
- There is no requirement to provide prior validation evidence of the accurate and reliable operation of the system in an offshore trial.

For the purpose of a WRA deployment, the evidence required consists of:

- The maturity evidence required for a FLS trial, as described immediately above;
- An additional requirement to provide validation evidence on wind speed and direction accuracy, and on reliability, from an offshore FLS trial, which would ideally have been carried

out in a manner as described in this document, specifically referring to the trial assessment recommended practice (see Section 7);

- The validation evidence should meet the criteria for a "Pre-Commercial" maturity level according to the OWA Roadmap [7], (Table 1A);
- It is noted that "Commercial" maturity level is attained only through multiple trials and deployments, and entails a lower uncertainty level concerning the wind resource assessment results. The degree to which a "Commercial" maturity level is necessary for a given WRA is a matter for judgement and should be assessed on a case-by-case basis.
- The validation evidence should meet the criteria for a "Pre-Commercial" maturity level, as described in Annex A.

RP 51: Suitability of FLS Dimensions and Weight.

Confirm that the dimensions and weight of the FLS (see RP 26) are compatible with the site layout (e.g. available space at quayside, water depth at low tide and including wave action, weight limitation of lifting equipment, permissible drift radius when deployed).

RP 52: Suitability of operating conditions.

It should be confirmed that the range of metocean and wind conditions that the supplier asserts the FLS is capable of operating in (see RP 27) is consistent with the expected conditions at the site. This should include consideration of the impact of extreme conditions. (Note that assessing whether accuracy is sufficiently likely to be acceptable under expected conditions is addressed by RP 59).

RP 53: Suitability of maintenance information and regime.

The information supplied on maintenance requirements and the maintenance regime should be reviewed for fitness-for-purpose by suitably qualified and experienced staff. It is recommended that the normal maintenance interval during deployment, including for replenishment of consumables, should be greater than 6 months. (It is recognised that preventative maintenance may be scheduled ahead of periods of inclement weather independently of this recommendation.)

RP 54: Suitability of Method Statement (MS).

The information supplied in the MS on how to deploy, commission, recover the FLS, and on how to perform component replacements, should be reviewed for fitness-for-purpose by suitably qualified and experienced marine operations staff. The MS should also detail operational procedures for dropped objects, emergency response and risk register.

RP 55: Protection from damage due to relative motion – power system.

Where there is relative motion between parts of the FLS, care should be taken to protect any component (e.g. data and power connectors) which may be exposed to wear.

Note 14: Oversizing components and redundancy

A general observation is that oversizing the capacity of systems (e.g. power generation, power storage, data storage, communication redundancy) and added redundancy with respect to the expected demands on them is an effective design policy promoting resilience of the system.

RP 56: Overall system evaluation – general.

The fitness-for-purpose of the overall system (including power systems, communications, data logging, ancillary measurement equipment, mooring, compatibility of work boats) and its transportation should be evaluated by a suitably qualified and experienced expert individual or organization, taking account of recognised risks (see Note 3, Note 7, Note 9).

4.3 LiDAR system

RP 57: Evaluating accuracy of the LiDAR type.

The type of LiDAR device used in the FLS shall have been tested in several well-documented tests prior to its integration. These onshore tests shall have been performed according to the guidelines in IEC 61400-12-1 (see Annex L of [12]), and the IEA Wind Recommended Practices for ground-based LiDARs [5], respectively, and the results shall be available to the user of the FLS. The results will be available as one or two parameter linear regressions in a good quality, peer-reviewed publication or otherwise be endorsed by qualified and experienced individuals who are independent from the LiDAR OEM. The level of accuracy demonstrated in these tests will be at least within the acceptance criteria for wind speed and accuracy from Table 3A. It is accepted that due to the specific details of the tests carried out, the metrics obtained may not be directly comparable with those in Table 3A however this is a useful guide.

RP 58: Wind industry acceptance of the LiDAR type.

The LiDAR type should have been used commercially for WRA purposes (e.g. for onshore projects, and/or offshore deployments on fixed platforms). Types that are considered by the manufacturer to be appropriate for operation in a marine environment, but have not been demonstrated in a marine environment, should be considered as inherently more risky.

Note 15: Evaluation of motion compensation – general.

There is a risk that the motion compensation or limitation arrangements on the FLS are not sufficient to avoid problematic deterioration of the wind speed and/or direction measurement accuracy. The evaluation can include design information, modelling data and trial data.

RP 59: Evaluation of motion compensation – FLS trial.

It is recommended that for a FLS trial deployment, there is convincing evidence that the motion compensation system has the *potential* to work effectively in the range of sea states to be encountered during the trial, and that the evidence provided to justify this potential should be reviewed by a suitably qualified person who is independent from the FLS OEM. Note that the range of motions experienced during the trial will be monitored and checked (Section 5.5 and 7.2).

RP 60: Evaluation of motion compensation – WRA deployment.

It is recommended that for an FLS deployment for WRA, there is convincing evidence that the motion compensation system has been *demonstrated* to work effectively in the range of sea states to be encountered during the deployment. Ideally this demonstration is in the form of offshore FLS trial results, which would have been carried out in the manner described in this document, specifically referring to the trial assessment recommended practice (see Section 7). As for FLS trials, each degree of freedom should be considered separately and evidence provided that the motion compensation (or justification for lack of motion compensation) has the potential to be sufficient; however in this case this should be supplemented by specific trials data. Ideally the range of sea states encountered in the trial would encompass the extremities of the range of sea states anticipated in the WRA deployment; also the trial deployment period would be as recommended (see Section 7). The degree to which a lesser range of sea states and/or a shorter trial deployment period can be accepted is dependent on the owner/operator's appetite for risk, and the acceptability level should be considered in this light.

4.4 Power System

RP 61: Power storage requirement.

For systems relying on renewable power sources, it is to be expected that the FLS will have to operate for some periods without any on-board renewable power sources generating power. It is therefore recommended that there is reserve power (e.g. in the form of batteries) for the system to operate fully for at least 1 week, and preferably for 2 weeks.

RP 62: Power system maintenance/replenishment requirement.

The maintenance interval recommended practice (see RP 53) implies that the power system should be able to operate autonomously for at least 6 months without replenishment (e.g. for fuel cells) or maintenance. This should be confirmed.

RP 63: Power system full recharge requirement.

Renewable power systems should be sized to provide a complete recharge of batteries, rather than just a top-up charge.

Note 16: Safe access to power system components.

Where wind charger units are deployed, consideration should be given to safe access for personnel, either by suitable location and guarding and/or by the use of shorting/furling procedures.

The safety of batteries should also be considered, especially the explosion risk caused by the use of lead acid batteries. Suitable ventilation systems and safe methods of inspection and access should be provided.

4.5 Data Logging and Communication

RP 64: Evaluating data logging capacity.

There should be sufficient data storage on-board to ensure that all data measured for the duration of the deployment is stored and recoverable after the trial, in the event that communication fails.

RP 65: Evaluating communication system redundancy.

The communication system should include at least two separate means of communication (e.g. through both satellite and 3G cell network communications). The type of communication used should switch automatically or otherwise be controllable without deploying personnel offshore.

RP 66: Evaluating communication system – wireless system.

A wireless communication system should be in place, such that a connection can be established from a workboat approaching but not necessarily attaching to the FLS. The wireless communication system should feature, as a minimum:

- The full range of data download and control features available in normal offshore/onshore communication;
- A reset capability for the LiDAR, logging system, communication system and power system.

4.6 Ancillary measurement equipment

RP 67: Evaluating wave sensor set-up.

Wave sensors capable of recording at least wave height and wave frequency (or period) over no longer than 30 minute intervals must be part of the FLS or recommended to be deployed separately as part of the measurement campaign. If the wave sensor is mounted on the buoy, a careful evaluation of whether the presence of and motion of the buoy could have a deleterious effect on the wave sensor should be made. For separate wave measurement system deployments, the separation distance should be no more than 500 m. The specific metocean characteristics which should be available are those also specified in Section 5.4.

RP 68: Evaluating secondary wind speed and direction sensors.

A secondary source of wind speed and direction measurement should be available as a cross check. An anemometer and a wind vane at approximately platform level (or ideally at the standard 10 m reference level), and free enough from obstruction to function as a functionality check, would be sufficient for example.

Note 17: Evaluation of inclinometers and other motion sensors – general.

Depending on the type of FLS, it may be advantageous to provide information on the inclination and/or orientation of the LiDAR. For example, if the FLS has been demonstrated to have good accuracy in moderate sea states, it may be advantageous to monitor the range of inclinations experienced (or rate of change of inclinations) for a new deployment in heavy sea states. No recommendations for monitoring are made. However the following may be considered:

- For a spar-buoy system which is not designed to incline by more than a few degrees, monitoring the maximum inclination recorded every 10 minutes;
- For a marine buoy where assumptions are made on the maximum angular rotation rates which is tolerable to maintain wind speed measurement accuracy, monitoring the inclination at 10 Hz and from this deriving the maximum angular rates experienced;
- For a buoy where the wind direction is in part derived from the orientation of the FLS relative to a global reference frame, monitoring the orientation of the FLS at 1 Hz.

4.7 Floating Platform

RP 69: Evaluation of the floating platform – safety systems

The provision for safe access, conducting offshore maintenance tasks, risk assessment, navigation lights and geo-location system should be assessed by a suitably qualified and experienced expert individual or organization. The expert should also assess the presence and fitness for purpose of any other applicable safety systems or process.

4.8 Mooring

RP 70: Evaluation of mooring design and arrangement suitability for site.

Even if a FLS has been successfully deployed before, it is not necessarily the case that the same combination of buoyancy, mooring cable length and FLS dimensions will be successful at another site with different seabed conditions, current, tide and depth characteristics. For this reason the suitability of the mooring arrangements should be reviewed for each proposed new site by a suitably qualified mooring design authority.

The mooring system consists in different elements such as foundation, anchor, mooring line and additional components (i.e. shackles, swivels, submerged or surface buoyancy and weights). All of this need to be designed to withstand both ultimate and fatigue load limit states. Guidance for relevant load conditions and analysis methodology for different setups and materials used can be found in e.g. IEC 62600-10, DNV-OSS-312, DNV-OS-E301 and DNV-OS-E303, see Table 2 in Section 2.8.

The design should be reviewed or may even need to be approved by the relevant local authorities.

RP 71: Evaluation of MS for mooring inspection.

Moorings should be visually inspected from anchor to fairlead annually. This inspection can identify worn links, line abrasions, and other damage.

4.9 Transportation of FLS to site

RP 72: De-risking shock damage to the LiDAR

If the LiDAR is transported as an integral part of the FLS then the FLS should be fitted with one or more shock sensors during transportation to the site to detect events that may damage equipment. A shock sensor should be affixed directly to the LiDAR unit to detect events that may damage the LiDAR. In each case an acceptable acceleration threshold should be agreed between the supplier and the owner/operator prior to transportation. Where mechanical motion compensation is used the motion compensation should be disabled during transportation to reduce the chance of unexpected motion.

5 Trial Campaign Design

5.1 Overview

This section describes recommended campaign parameters for the case where the purpose of the deployment is to trial a FLS, and refers to the OWA Roadmap [7]. Note that this is distinct from a FLS deployment for the purpose of Wind Resource Assessment (WRA), see Section 6. The assumed purpose of the trial is to assess the capability of the FLS to accurately and reliably measure wind speed and direction. This necessitates the use of a trusted reference measurement system for wind speed and direction. Specification for recommended reference measurement systems is included in this section.

This section is structured as follows:

- Confirming correct and accurate operation of equipment prior to deployment on a trial is described in Section 5.2.
- A discussion of a suitable location for the trial is included as Section 5.3.
- The recommended equipment and facilities are described in 5.4. This includes the reference wind speed and direction measurement system, and a metocean measurement system.
- The quantities which should be measured are described in Section 5.5.
- Recommended functionality checks to avoid the risk of using damaged or poorly operating equipment are described in Section 5.6.
- Data monitoring which should be performed during the trial is described in Section 5.7.
- Confirming that measurement equipment has not deteriorated after the trial is described in Section 5.8.

Note that the closely related topic of performing the comparison between FLS wind data and those from the reference system (as well as a consideration of availability) is described in Section 7.

<u>RP 73: 'Blind' trial principle.</u>

To avoid any doubt on the integrity of the trial, the suppliers of the FLS system or any other actors in its deployment should ideally not have any visibility of data from the reference system until FLS data have been supplied to the adjudicator for the equivalent period. This may not always be possible, in which case independent measures should be taken to verify integrity of the reference data, FLS data, and the comparison of the two data sets.

<u>RP 74: Feedback on performance</u>

The FLS supplier should have access to the FLS data throughout the campaign, without violating the blind trial principle. Feedback from the reference system should be provided during the first two weeks of deployment and at regular intervals throughout the campaign to ensure that the FLS is performing as expected.

5.2 Pre-deployment Checks

RP 75: LiDAR unit pre-deployment verification (FLS trial).

The guidelines in IEC 61400-12-1 CDV / Annex L [12] should be followed to establish confidence in the accuracy of the LiDAR unit to be used in the FLS trial:

- The LiDAR is tested against a measurement mast equipped with standard anemometry.
- Based on the collected measurement data, a verification test or accuracy assessment is performed.
- The verification test shall be performed for each individual system before application in the trial. A system classification is necessary only for each type of system, as specified in IEC 61400-12-1 CDV [12] .

Note that these IEC guidelines do not in themselves provide acceptance criteria for the unit under test, rather they are guidelines for the manner in which the verification check should be conducted. For this reason, it is useful to supplement these guidelines with data coverage criteria e.g. from the NORSEWInD trials [13] and accuracy acceptance criteria from the OWA Roadmap [7] as shown in Table 3A.

5.3 Location

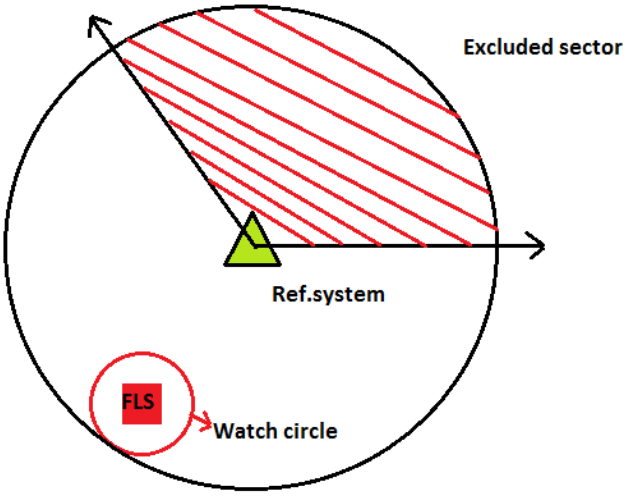


Figure 6: FLS deployment avoiding excluded sector. The green triangle represents a fixed platform on which the reference system is mounted. The hatched sector is not permissible for FLS deployment as it is required to access the fixed platform. The deployed location for the FLS including the watch circle is also indicated.

RP 76: Ideal location for a FLS trial

The location for a FLS trial has the following recommended characteristics:

- Minimal variation in the wind resource across the site, to facilitate comparison of measured data from the FLS and the reference system;
- A similar wind and metocean climate to the target site or sites for subsequent WRA deployment of the FLS;
- The presence of a sector where the FLS can be deployed without conflicting with operational issues. Such a set-up is indicated in Figure 6.

Note 18: Ideal location for a FLS trial

It is not always possible to carry out a trial in an ideal location. Non-ideal circumstances can include, for example, a suspected variation of wind resource across the site due to coastal effects, or relatively benign wind and wave conditions compared to the target site for WRA deployment. In such cases, it is likely that a worthwhile FLS trial can still take place, but that care must be taken in interpreting the data, and there is likely to be an increased uncertainty compared to the ideal case. A description of the site should be available and known influences should be clearly stated.

5.4 Equipment and facilities

Note 19: Reference system for wind speed and direction.

The reference system for wind speed and direction could be an offshore met mast, or any other trusted reference measurement system mounted as the situation allows, for example: onshore met masts or LiDARs; met masts or LiDARs on piers, lighthouses, or other offshore structures, etc. The key concern is the uncertainty in the wind speed and direction measurement, which should be at an acceptable level (as assessed by a suitable expert). It should be noted that the uncertainty of the FLS measurements derived from the trial results cannot be lower than the uncertainty of the reference system measurements. IEC 61400-12-1 CDV Annex L details a method for determining absolute uncertainty [12] , which is also the basis for the FLS uncertainty assessment according to section 7.6 in this document.

RP 77: Specification of the reference system.

Specifications and associated data for the reference system must be available. The effects of the mast structure, foundations and platforms or other flow distorting features on the reference measurements should be well understood and documented (for example mast and boom effects, possible effects of the sub-structure and platform). Furthermore, the influence of the site itself (e.g. topography) on reference measurement uncertainty should be well understood.

- Mechanical and ultrasonic anemometry systems should be designed and installed in accordance with IEC 61400-12-1, see [3]. The measuring instruments (anemometers and wind vanes) should be suitably calibrated by an accredited calibration laboratory within the last 12 months.

- It is recognised that the OWA Roadmap [7] does not refer to the use of other reference systems, namely remote sensing devices, as suitable. Here it is considered that technology maturity has developed sufficiently to consider remote sensing devices as suitable references, assuming that the measurement campaign is carried out by suitably qualified and experienced experts or organisations.

- For the case of other reference systems, industry best practice for set-up should be followed; if the reference systems are LiDARs then the guidelines in references [5] and [12] should be followed. In that case it is important that the equipment and power supply be such that the reference LiDAR may operate for extended periods without disturbance and interruption in highly challenging environments and that the influence from the support structures (for offshore platforms) or from the ground (on-shore/ near-shore installation) on the reference instrument are negligible or well understood.

RP 78: Separation distance between FLS and reference system.

To achieve a high comparability between the FLS and reference measurements, the separation distance should be minimised, while respecting the relevant safety restrictions. In general a separation direction aligned with the prevailing wind is preferred to a separation direction which is transverse to the prevailing wind. In past trials a separation distance of 500 m has been used successfully so this is the current recommendation. It is considered that if a separation distance of less than 500 m were used in a well-configured trial, poor agreement between reference and FLS data would not be attributed to too small a separation distance. Conversely, for greater separation distances it is unlikely that doubt would be introduced to trial results in good agreement; however trial results in poor agreement would be difficult to attribute to large separation distances or other factors. The recommended setup of FLS and reference system is depicted in Figure 7.

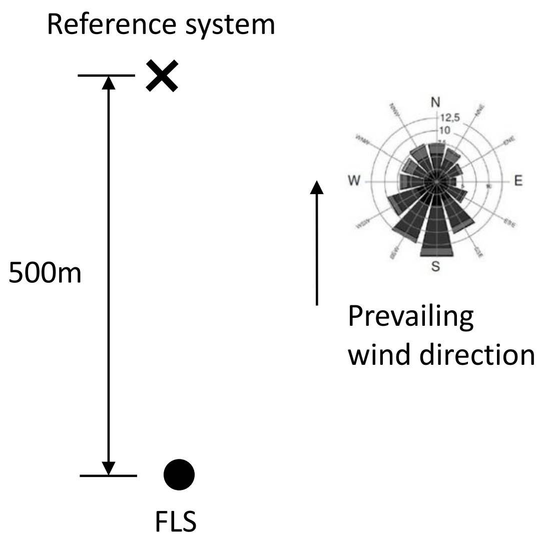


Figure 7: Recommended setup of FLS and reference system with respect to distance and direction

RP 79: Positioning to ensure undisturbed flow.

Both the FLS and the reference system should be subject to an undisturbed flow, i.e. a valid measurement sector shall be defined in a way that neither the measurements of the FLS nor those of the reference system are affected by wakes of surrounding wind turbines or other obstacles.

RP 80: Metocean measurement system.

Measurements of the oceanographic conditions should be made sufficiently close to the FLS under test such that they are representative. These should be taken using an industry accepted and time proven system which has been suitably maintained and calibrated in line with the manufacturer's guidance.

The dataset provided by the Metocean reference system should cover at least:

- Significant wave height;
- Peak wave period;
- Mean wave height;
- Wave spectra;
- Current speed (at different positions over the water depth);
- Current direction;

- Water level;
- Sea water temperature.

These parameters should be recorded at measurement intervals of no longer than 30 minutes.

RP 81: Ancillary measurement system.

If supplementary measurements are required as part of the validation process (such as air temperature, humidity, barometric pressure etc), instrumentation must be installed and operated in line with the manufacturer's guidelines and industry best practice. Instruments must have been calibrated by an accredited calibration laboratory and remain in calibration for the period of the trial.

RP 82: Synchronisation of data loggers.

Data loggers on the FLS and reference system should be time synchronised to a common public source (such as GPS time, radio signal, or other global reference source), such that an offset or drift between the FLS and the reference system throughout the course of the trial is minimised.

5.5 Measured Quantities

The quantities of most fundamental importance are wind speed and direction. At the simplest level, the accuracy of the FLS will be assessed by comparing the wind speed and direction measurements from the FLS with those from the reference system, and the reliability of the FLS as a measurement device will be assessed on the availability of these data.

RP 83: Measured Quantities - Datum.

For all quantities which are made at a specific height, including wind speed and direction, the height should be reported as well as the datum used, for example mean sea level. It is recommended that the datum of the measurement height of FLS and reference system is the same, see Figure 8.

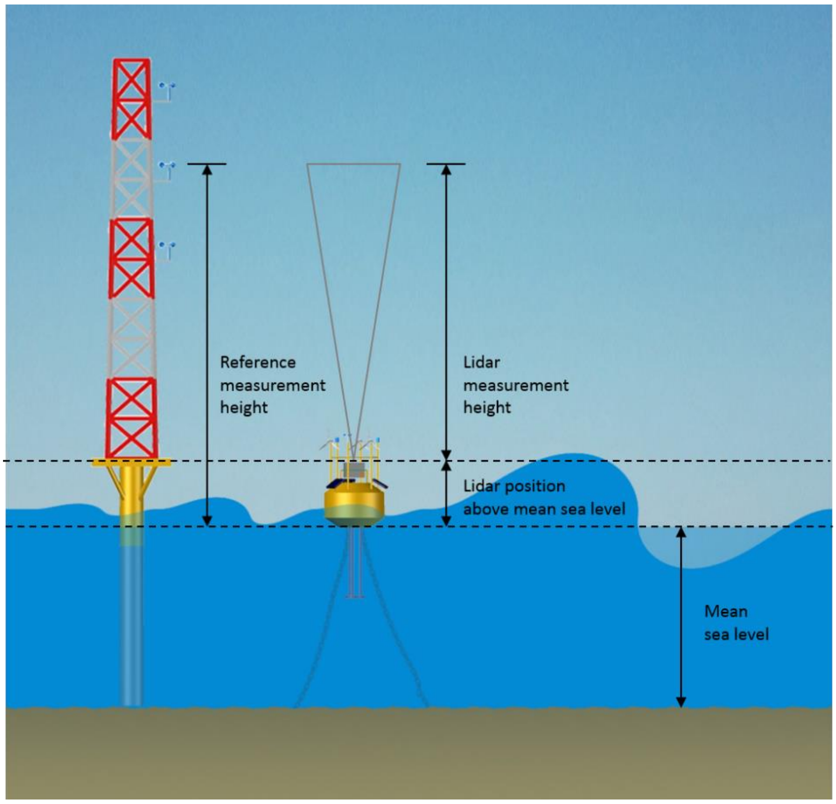


Figure 8: The datum of the measurement height of the FLS and the measurement height of the reference system should be the same, for example mean sea level.

RP 84: Measured Quantities - Comparison.

The FLS and the reference system should measure wind speed and direction at a range of heights as follows:

- Wind speed (m/s) should be recorded as a 10 minute average;
- Wind direction (degrees) should be recorded as a 10 minute average.

In addition, it is recommended to also record minimum, maximum and standard deviation values, within these 10 minute periods, for these quantities. This presents an opportunity to investigate turbulence measurements and to perform additional functionality checks.

It is further good practice to publish the amount of data measured in each of the data bins and to report the amount and location of any data that has been excluded through post-processing or filtering.

Note that the above is consistent with the OWA Roadmap [7].

RP 85: Measured Quantities - Sensitivity.

Other quantities are used to assess the sensitivity of the wind speed and direction correlations to site conditions. The quantities that should be measured for this purpose include:

- Significant and maximum wave height (m) should be recorded as an average over 30 minutes or less;
- Peak and mean wave period (s) should be recorded as an average over 30 minutes or less.

Also, tide height (with respect to MSL) should be available for the trial site and the duration of the trial, noting that this is often available from sources not related directly to the trials equipment. It is also recommended to record a number of other environmental and FLS-related quantities for the purposes of sensitivity analysis. It is not possible to generalise further as their importance or otherwise will depend on each case; for example, for a FLS which is designed to isolate the LiDAR from angular motions, it may be important to measure the motion of both the buoy and of the LiDAR if there is a lack of other substantiation. Such quantities where it is advisable to consider taking measurements are as follows:

- Inclination (pitch, roll, yaw) of the platform (and of the LiDAR if isolated or compensated from the platform motion);
- Translational accelerations (heave, surge, sway) of the platform (and of the LiDAR if isolated or compensated from the platform motion);
- Rotational accelerations (rate of change of pitch, roll, yaw) of the platform (and of the LiDAR if isolated or compensated from the platform motion);
- Current speed;
- Air and water temperature;
- Humidity;
- Cloud cover, mist/fog, visibility;
- Precipitation.

Lastly, as described in Section 2.3, LiDAR quality criteria may be provided in a manner such that the end user can apply a variable quality threshold, e.g. to CNR. In such a case it is recommended to perform a sensitivity study with respect to available variable quality criterion thresholds.

Note 20: Measurement heights for wind speed and direction in a trial.

Ideally, wind speed and direction as measured by the FLS and the reference system will be compared at a number of heights within a range equivalent to a contemporary large turbine’s rotor disk minimum and maximum heights, as well as including the hub height. It is recognised that this may not be practically possible, and that a smaller range may still result in very useful trial data.

However, if as a minimum the hub-height level cannot be attained, this is far from ideal as this introduces a significant degree of uncertainty: firstly, hub-height wind speed is still seen by the industry as the key parameter, and a vertical extrapolation would have to be performed to estimate the wind speed at hub height; second, for some systems potential sources of inaccuracy due to FLS motion may be a function of beam length/height, and may not become evident for short beam lengths/lower heights.

RP 86: Recommended measurement heights for wind speed, wind direction and wind shear in a trial.

The reference system should measure wind speed and direction at a range of at least four heights, with a maximum not less than hub-height of a contemporary large turbine; one of the measurement heights should be equivalent to hub-height. As measuring shear is of interest it is advisable to set up the lowest measurement height to be the minimum height achievable given the practical limitations e.g. the combination of measurement platform height and minimum LiDAR beam height is likely to dictate this. Hub-height minus 40 m is generally acceptable as a height from which useful shear measurements can be made. The ranges of the LiDAR on the FLS under trial should be configured to match these heights, with MSL as the reference height.

RP 87: Recommended trial duration.

A six-month trial duration is recommended for the following reasons:

- This should provide adequate data coverage to perform a meaningful correlation of wind speed and direction measurements.
- A more demanding requirement in terms of data coverage is that pertaining to metocean conditions; it is considered likely that a representative range of conditions may not be attained for a shorter trial duration. This particularly applies as such a trial at the same time should serve as system classification, providing representative information on possible sensitivities of the FLS behaviour to various Environmental Variables (see section 7.6, RP 106).
- A WRA deployment is likely to last for more than six months. Therefore the system should demonstrate its reliability for at least six months.
- It is recognised that accuracy and reliability aspects of the FLS should ideally be trialled simultaneously, as in prospective WRA deployments there are simultaneous demands on accuracy and reliability.
- The most straightforward way to meet all of these considerations is for a single six-month trial period.

However it is recognised that a six-month trial is not always practical to achieve, and accuracy and reliability evidence from some other combination of trial deployments may be considered as equivalent. However this evidence should be considered and justified on a case-by-case basis.

Note 21: FLS trial in winter months

A requirement for a winter months trial deployment in order to experience the greatest possible range of environmental conditions is often discussed. This is frequently preferable, but should not be considered as an absolute requirement for all cases. Rather, this should be considered on a case-by-case basis with reference to possible sensitivities of the FLS behaviour to various Environmental Variables (see section 7.6, RP 106).

5.6 Functionality Checks

Note 22: Functionality checks at the outset of a trial

There is significant risk that in transportation or installation some damage or misalignment of the measurement systems occurs. Therefore the trial procedures should include checks of the correct operation of all systems immediately after deployment to the final trial location and switching on. The FLS supplier should include such procedures for their own systems as part of the Method Statement. Equivalent procedures should be in place for the reference system and ancillary measurement equipment (which is likely to be the responsibility of the trial operator rather than the FLS supplier). Note that these functionality checks should not violate the principle of the "blind" trial. Particular attention is required to any LiDAR and/or FLS set-up necessary to determine wind direction as this has been a source of significant error in some deployments: a deployment procedure should be provided as part of the MS (see RP 29); how orientation/wind direction is calculated should be well understood (see RP 30); and, how any necessary confirmation of FLS orientation should be achieved during deployment should also be detailed (see RP 48).

5.7 Monitoring during Deployment

Note 23: Regular monitoring during trial.

Experience has shown that it is prudent to regularly monitor a FLS during deployment so that any problems that emerge can be remedied at the earliest opportunity.

RP 88: Recommended monitoring during trial.

The following monitoring of the FLS is recommended during the trial:

- Data availability.
- For the indicated wind speed and direction, that they are realistic values.
- The functioning of the on-board power system e.g. voltage levels in any batteries, and/or evidence of renewable power sources being effective.
- Any available LiDAR data quality criteria (e.g. CNR, spatial variation, etc.)

- Location of the FLS to check it is within the expected drift radius.

It is recommended that such checks are performed on a daily basis in the first two weeks of deployment, and subsequently on a weekly basis as a minimum. This monitoring should form part of the maintenance management plan for the FLS and should include alerts that will trigger reactive interventions.

5.8 Post-Deployment Checks

Note 24: Post-deployment checks.

Once a LiDAR unit has been established as sufficiently accurate (see Section 5.2), there is no clear reason for suspecting that its accuracy will degrade in a systematic manner during the trial and compromise the trial results. Therefore it is not normally recommended to perform a post-trial verification check on the LiDAR unit. Circumstances which may result in a decision to perform a post-trial validation are for example if a doubt has arisen through an accident or impact affecting the LiDAR during the trial.

6 Wind Resource Assessment Campaign Design

6.1 Overview

This section describes recommended campaign parameters for the case where the purpose of the deployment is to support wind resource assessment. Note that this is distinct from an FLS deployment for the purpose of trialling a FLS (see Section 5). Many of the recommendations are the same or related to those presented in Section 5. In this section it is also recommended to use a trusted reference measurement system for wind speed and direction; however in this case this is for a shorter duration as part of pre-deployment checks, rather than as the primary purpose of the FLS deployment.

This section is structured as follows:

- Confirming correct and accurate operation of equipment prior to deployment on a trial is described in Section 6.2.
- A discussion of a suitable location is included as Section 6.3.
- The recommended equipment and facilities are described in 6.4. This includes the reference wind speed and direction measurement system, and a metocean measurement system.
- The quantities which should be measured are described in Section 6.5.
- Recommended functionality checks to avoid the risk of using damaged or poorly operating equipment are described in Section 6.6.
- Data monitoring which should be performed during the trial is described in Section 6.7.
- Confirming that measurement equipment has not deteriorated after the trial is described in Section 6.8.

Note that the closely related topics of performing the comparison between FLS wind data and those from the reference system for the pre-deployment check (as well as a consideration of availability), and assessment of the wind data itself, are described in Section 8.

The blind trial principle, which is described in Section 5.1 for FLS trials, also applies here for the pre-deployment check of the FLS.

6.2 Pre-Deployment Verification

<u>Note 25: Pre-deployment verification: assumptions and definitions</u>

In this section recommendations and notes are made on the topic of pre-deployment verification for FLS units. Figure 9 summarises the content of this subsection. Some assumptions and definitions are included below:

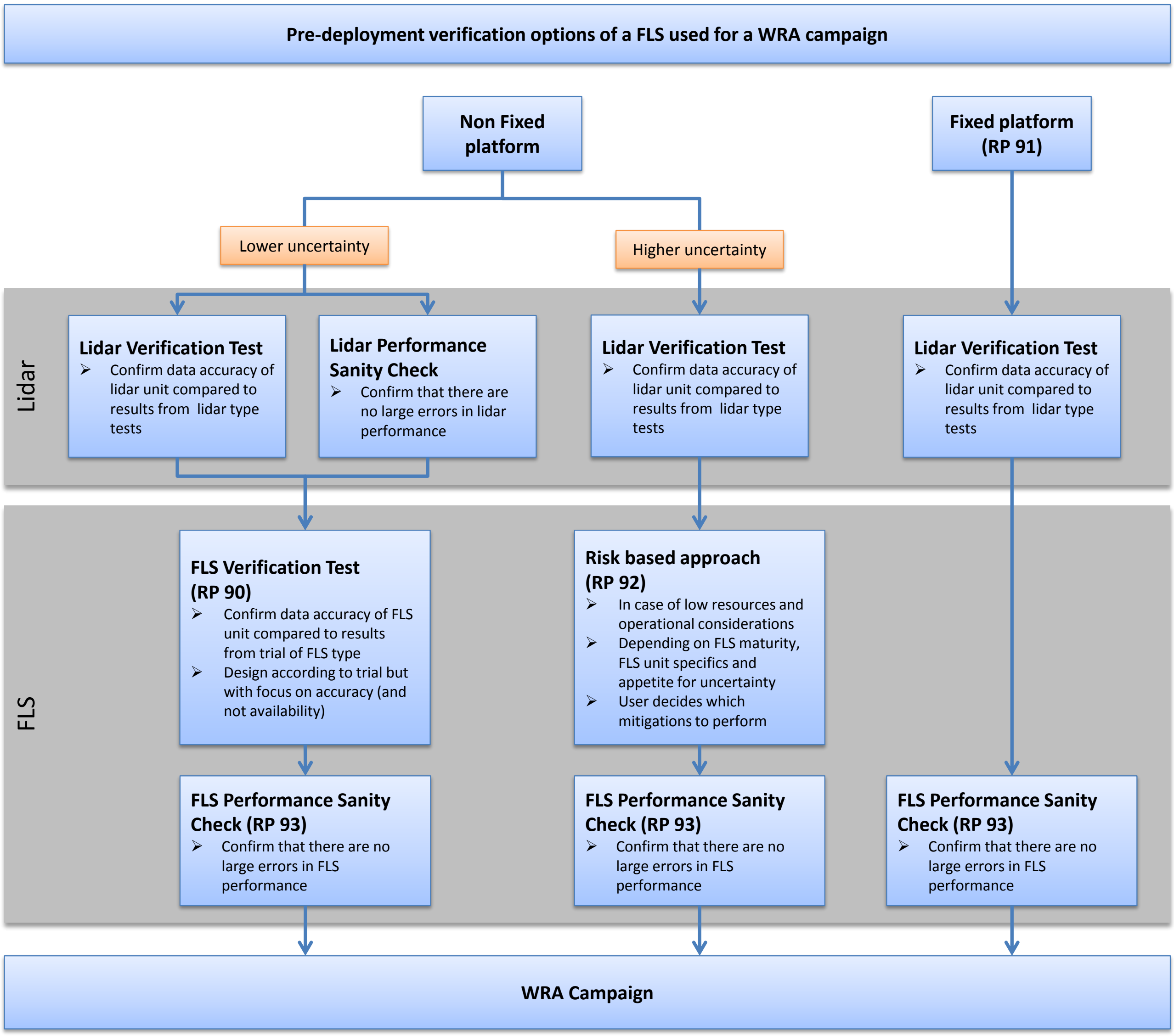


Figure 9: Summary of pre-deployment verification recommendations and options

- It is assumed that the LiDAR unit to be used is of a recognised, industry proven type which has demonstrated sufficient accuracy (see RP 57).

- It is assumed that the FLS type that is to be deployed for WRA purposes is of a type which has previously been the subject of at least one offshore trial (see Sections 5 and 7). It is also assumed that the maturity level of the FLS type has been assessed as either "Pre-Commercial" or "Commercial" as defined in the OWA Roadmap (reference [7]), as discussed in Section 4.2.

- A **LiDAR Verification Test** is a test carried out on a LiDAR unit (where measured data are compared to a trusted reference measurement) which is designed to confirm that wind data accuracy is acceptable and commensurate with that achieved in previous tests of the same LiDAR type. The requirements for the verification test are described in RP 75.

- A **FLS Verification Test** is a test carried out on a FLS unit (where measured data are compared to a trusted reference measurement) which is designed to confirm that wind data accuracy is acceptable and commensurate with that achieved in a previous offshore trial or trials of the same FLS type. The test should be designed in the same manner as described in Section 5, but with the focus on accuracy and without the requirement for assessing availability; however, it is assumed that the FLS operates continuously and error-free during the whole verification test period. In other words, as long as the wind speed bins are filled, which typically will take 4 to 8 weeks, then an accuracy assessment can be performed.

- A **LiDAR Performance Sanity Check** is a check carried out on a LiDAR unit which is designed to confirm that there are no large errors in the LiDAR performance, but to a lower standard and of a shorter duration than a LiDAR Verification Test. This is typically a de-risking activity to confirm that operational activity (e.g. transportation or installation) has not introduced performance problems. The sanity check consists of comparing the measured data with data from another source, which may be nearby independent instrumentation or even remote instrumentation suitably interpreted. The suitability of data sources, the measurement duration and the required data agreement and interpretation should be evaluated by a suitably skilled and experienced organisation on a case-by-case basis.

- A **FLS Performance Sanity Check** is a check carried out on an FLS unit which is designed to confirm that there are no large errors in the FLS performance, but to a lower standard and of a shorter duration than a FLS Verification Test. Other considerations are as for the LiDAR Performance Sanity Check.

Note 26: LiDAR unit pre-deployment verification (WRA deployment).

The primary recommendation concerning verification of the measurement system is to perform an FLS Verification Test (see RP 89). In this way, LIDAR data accuracy is assured by a successful outcome from the FLS Verification Test, and a LIDAR Verification Test is not required.

However, this consideration is from the data accuracy and uncertainty point of view, and does not consider project risk. Before carrying out a FLS Verification Test, the risk that the FLS unit performance is found to be unsatisfactory should be considered. If this were attributable to poor LiDAR performance, an expensive and time consuming FLS Verification Test could have been avoided by carrying out a LiDAR Verification Test, or perhaps by performing a lower standard of check on the LiDAR unit's performance. This risk should be considered on a case-by-case basis when planning a FLS Verification Test:

- If this risk and impact are considered as fairly high, a LiDAR Verification Test should be considered before the FLS Verification Test;

- If the risk and impact are considered as moderate or low, a LiDAR Performance Sanity Check should be considered before the FLS Verification Test.

Note that in the case where an FLS Verification Test will not be carried out (see RP 90), then a LiDAR Verification Test is clearly recommended.

<u>RP 89: FLS Verification Test within one year of WRA deployment</u>

It is recommended that the FLS unit undergoes a FLS Verification Test (see Note 25) no greater than one year prior to commencing the WRA deployment. This provides measured data traceability back to the trusted reference system. It is recognised that it may not always be possible to perform an FLS Verification Test due to project constraints, in which case an alternative risk-based approach is recommended, see Note 27 and

RP 91RP 91. Note also that in such a case, with reference to the discussion in Note 26, it is recommended that a LIDAR Verification Test is carried out.

RP 90: Alternative traceable approach for "fixed" FLS platforms

For FLS configurations which are stationary, or very close to being stationary, an alternative approach can be employed. This differs from RP 89 in two main elements:

- The platform or buoy is considered to be static, therefore the FLS configuration is analogous to mounting a LiDAR on a fixed offshore platform;
- The verification and traceability considerations are therefore centred on the LiDAR unit, not the FLS unit.

For this alternative approach to be considered, the following criteria must be met:

- The buoy design is fundamentally static in nature, i.e. not following the wave motion.
- There is no motion compensation system.
- In at least one FLS trial, the FLS type has demonstrated no significant sensitivity (see Section 7.6) to wave motion parameters.
- In at least one FLS trial (see Section 5), the range of motion of the LiDAR has been recorded.

If these conditions are met, the LiDAR Verification Test (see Note 25) should suffice for traceable uncertainty estimation. Note that during the subsequent WRA deployment, the range of LiDAR motion must also be recorded, to confirm that the motion envelope from the trial is not exceeded.

Note 27: Risk-based approach to determining appropriate pre-deployment verification

It is recognised that operational considerations and available resources may mean that a decision is made not to follow recommendation RP 89, and that the particular case of RP 90 may not be appropriate. A lesser standard of pre-deployment verification is highly likely to result in more uncertainty in the data. In the RP below some qualitative guidance is provided to aid decision making in balancing pre-deployment verification thoroughness with wind data uncertainty on a case-by-case basis.

RP 91: Risk-based approach to determining appropriate pre-deployment verification

A risk-based approach is recommended in determining appropriate pre-deployment verification actions. The purpose of the pre-deployment check for the FLS unit is not to establish that the type is capable of good performance – this has already been examined in the FLS trial or trials. Rather, it is to establish confidence that the specific FLS unit performs as well as the one which was trialled. Table 3 summarises the risks to the FLS unit under-performing compared to the unit that was trialled. Depending on the maturity of the FLS, the FLS unit specifics (e.g. motion compensation or not, mooring design changed or not) and appetite for uncertainty in the final data, the user should use this table to be guided on which mitigations to perform based on how much the risk is reduced. This table also refers to RP 89 and RP 90 and allows them to be understood in a risk-based context.

RP 92: FLS Performance Sanity Check

In all cases where an FLS unit is deployed to the offshore site for FLS purposes, there is always a risk that damage or poor installation has a negative effect on FLS performance. For this reason, a FLS Performance Sanity Check (see Note 25) should be carried out.

Risk and Risk Level (H=High, M=Medium, L=Low, VL=Very Low)	Mitigation	Advice and Risk Level after mitigation
Although the FLS unit is in theory identical to that trialled, in reality the **FLS system integration** is implemented differently, or to different quality, than the FLS used in the FLS trial (i.e. as in the type validation); this fact is not known, and has a negative impact on accuracy. *Risk Level:* Pre-Commercial: M Commercial: L	1. Perform a pre-deployment FLS Verification Test, as described in RP 89 thus providing traceability. 2. Perform an FLS Performance Sanity Check only. 3. For stationary FLS, apply RP 90 if possible.	1. *Risk Level:* Pre-Commercial: VL Commercial: VL 2. *Risk Level:* Pre-Commercial: M Commercial: L 3. *Risk Level:* Pre-Commercial: VL Commercial: VL
The **dynamic response of the buoy** is different in the deployed location compared to the FLS trial location due to (known) differences in the set-up, e.g. moorings, buoyancy, gimbal settings, software differences; this results in different and possibly lower accuracy. *Risk Level:* Pre-Commercial: H Commercial: M	4. Perform a pre-deployment FLS Verification Test, as described in RP 89. 5. For stationary FLS, apply RP 90 if possible.	4. *Risk Level:* Pre-Commercial: L Commercial: VL 5. *Risk Level:* Pre-Commercial: L Commercial: VL
The **dynamic response of the buoy** is different in the deployed location compared to the FLS trial location due to **differing, more severe sea states**; and has a negative impact on accuracy (whether motion compensation is employed or not). *Risk Level:* Pre-Commercial: H Commercial: M	6. Use the practices detailed in the Uncertainty sections (section 7.6) to extrapolate measured uncertainties to other sea state ranges, or adopt alternative approach. 7. For stationary FLS, apply RP 90 if possible. 8. For FLS which do not use motion compensation (be they substantially static or moving with the waves), the LiDAR or buoy motion can be recorded	6. *Risk Level:* Pre-Commercial: M Commercial: L 7. *Risk Level:* Pre-Commercial: > Data inside motion envelope: L > Data outside envelope: H Commercial: > Data inside motion envelope: VL > Data outside motion envelope: M 8. *Risk Level:* Pre-Commercial: > Data inside motion envelope: L > Data outside envelope: H

	in the WRA deployment and compared to that recorded in the trial(s). Staying within the same envelope confirms low risk data, data outside the envelope should be treated differently. For FLS which do use motion compensation, an equivalent approach can be used, but the motion of the LiDAR itself (not the buoy) should be used.	Commercial: > Data inside motion envelope: VL > Data outside motion envelope: M

Table 3: Risk-based approach to pre-deployment verification.

6.3 Location

The location of the deployment for WRA is determined by project requirements and needs to be fixed as early as possible in order to account for present site conditions which may be relevant for mooring design, see RP 18.

Note 28: Ideal location for FLS pre-deployment verification (prior to WRA deployment)

The location is subject to the same consideration as for the FLS trial (Section 5.3). In addition, the location should be such that any subsequent transport to the WRA site can be carried out with minimal disturbance to the FLS system. Note that even with a pre-deployment verification there is still in principle a risk that the system will not perform as well at the WRA location as it did at the pre-deployment check location due to factors which have to be changed or tuned between locations (e.g. the tuning for gimbals, mooring systems). As far as possible the FLS should have the same set-up at the pre-deployment site as it does at the WRA site. Every deviation from this, due to differences in location attributes or otherwise, should be recorded and justified.

6.4 Equipment and Facilities

The considerations and recommendations for equipment and facilities are as for the FLS trial (see Section 5.4), with the observation that in this case the reference system pertains to that used in the pre-deployment verification.

6.5 Measured Quantities

The considerations and recommendations for measured quantities are the same as for the FLS trial (see Section 6.5), with the following distinctions:

- In this case the reference system means the reference system used in the FLS pre-deployment verification.
- The duration of the pre-deployment verification of the FLS is a matter for expert judgement (see Section 6.2).
- The duration of the deployment for WRA is determined by project requirements.

6.6 Functionality Checks

The considerations and recommendations for functionality checks are as for the FLS trial (see Section 5.6). See also RP 92.

6.7 Monitoring during Development

The considerations and recommendations for monitoring during deployment are as for the FLS trial (see Section 5.7).

6.8 Post-Deployment Checks

<u>RP 93: Post-deployment checks – LiDAR unit</u>

It is not generally recommended that the pre-deployment check for the LiDAR unit (see section 5.2) should be repeated after the WRA deployment, despite this being inconsistent with MEASNET advice (see Annex C of [14]). An exception to this would be if for any reason doubt has arisen on the LiDAR unit performance during the trial.

<u>Note 29: Post-deployment checks – FLS unit</u>

It is not normally necessary to perform a post-trial verification check on the FLS unit. Circumstances which may result in a decision to perform a post-trial validation are for example if a doubt has arisen through an accident or impact affecting the FLS during the trial. Also see Section 5.8.

7 Trials Results Assessment

Section 5 describes recommended practices for trialling a FLS. Having carried out such a trial, the question arises as to how to best assess the results. This section describes the required data processing and comparisons and also relevant compliance and acceptance thresholds. This section also refers to the OWA Roadmap [7] with respect to wind speed and wind direction accuracy assessment and related acceptance criteria.

7.1 Overall Approach and Independence

Note 30: Overall approach for assessing wind speed and direction accuracy, and availability

The OWA Roadmap [7] for FLS recommends methods to assess wind speed and direction accuracy and defines acceptance thresholds based on Key Performance Indicators (KPIs). The Roadmap KPIs are based on industry practice and experience and have been generally accepted as a useful yardstick by FLS device suppliers and wind farm developers alike. In a similar manner, the Roadmap defines availability metrics which are widely used. In the current collection of recommended practices, it is considered that there is no pressing need to re-assess the methods and KPIs of the Roadmap, therefore they are followed faithfully (for wind speed and direction accuracy, and for availability). Nonetheless, as the body of FLS trial data has grown significantly since the Roadmap was first introduced, it is considered worthwhile in the near future to review the Roadmap criteria in the light of this data; as such this proposal is noted as a recommendation for future work (see Section 9).

RP 94: Independence of trial results

The FLS trial and the results of the data analysis should be reviewed by a suitably skilled and experienced independent organisation (i.e. independent from the FLS OEM) in order for the trial to be credible. This review should include verification of the correct execution of the measurement campaign design, and review of data capture and analysis.

7.2 Wind Speed, Wind Direction and Wind Shear Accuracy

RP 95: Wind speed, wind direction and wind shear correlations

Wind speed, wind direction and wind shear accuracy will be assessed using correlations of FLS and reference measurement system data. Only data from pre-defined sectors with undisturbed flow should be used.

Only post-processed data qualified as “good” by the system should be used, after application of quality filters defined by the LiDAR supplier. Ten minute averaged data will be used, and an ordinary least-squares linear regression created. Each valid wind speed data point from the FLS will be cross-correlated with the equivalent reference measurement system data (i.e. with the equivalent time stamp). For wind speed and wind shear correlations the y-intercept will be set to zero (i.e. a single-variant regression of the form $y=mx$). For wind direction correlations the y-intercept will be permitted to be non-zero (i.e. a two-variant regression of the form $y=mx+c$). Examples are shown in Figure 10 and Figure 11. Correlations should be produced in this way for the following data:

- Wind speed:
  - All wind speeds >2 m/s;
  - Wind speeds in the range [4 – 16] m/s.
- Wind direction:
  - All wind directions, all wind speeds >2 m/s.
- Wind shear exponent:
  - All wind speeds >2 m/s.

The appropriate measurement heights are described as follows:

- The wind speed correlations should be carried out for all available measurement heights, i.e. where at a certain height a wind speed measurement is available from both the FLS and from the trusted reference system.
- The wind direction correlations should be carried out for all available measurement heights, i.e. where at a certain height a wind direction measurement is available from both the FLS and from the trusted reference system.
- The wind shear parameter correlations should be carried out in relation to at least two measurement heights, two measurement heights being required to calculate the shear exponent, and the difference between these two heights should not be less than 40 m. These measurement heights should both be available from the FLS data and from the trusted reference system data (for recommendations on the heights to select, see section 5.5).

In creating wind direction correlations, care should be taken to manage "wrap-around" data points correctly. For example, if at a certain time a wind vane on a mast records a wind direction of 1°, and the FLS records 359°, it is advised to translate the latter value to -1° before evaluating the correlation.

<u>RP 96: Calculating the wind shear exponent</u>

The magnitude of the wind shear exponent α shall be calculated using the following equation (see also [4]):

$$\alpha = ln\ (\ v_1 / v_2\ ) / ln\ (\ z_1 / z_2\ ) \qquad \text{Equation (1)}$$

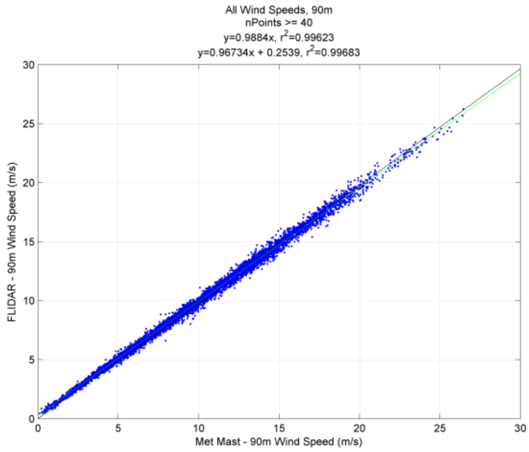
In the above equation, the measured heights above the reference datum (e.g. sea-level, see section 5.5) are denoted z_1 and z_2 respectively, and the measured wind speed at those heights are denoted v_1 and v_2 respectively. For recommendations on the heights to select, see section 5.5. Electing to use more than two heights in the shear exponent calculation is allowable. In such a case the data from the FLS and from the trusted reference system should be treated consistently.

RP 97: Data coverage requirements for wind speed, wind direction and wind shear correlations

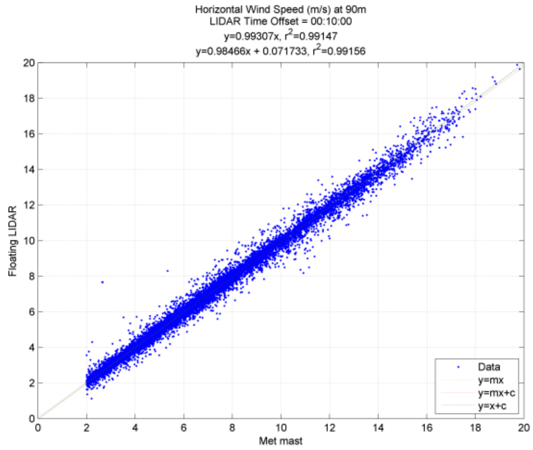
There is a minimum requirement on the data coverage required to achieve a meaningful correlation. At least 40 data points are required in each 1m/s bin between 2 m/s and 12 m/s, and at least 40 data points are required in each 2 m/s bin between 12 m/s and 16 m/s.

RP 98: KPIs for wind speed, wind direction and wind shear accuracy

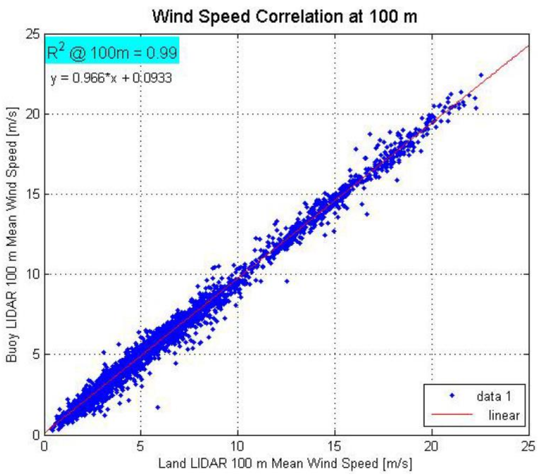
The Key Performance Indicators (KPIs) for wind speed and wind direction are the coefficients returned from the ordinary least-squares regressions performed on the data, as summarised in Table 3A. Note that there is no KPI for wind shear accuracy, which is discussed in Appendix C: Wind Shear KPI.



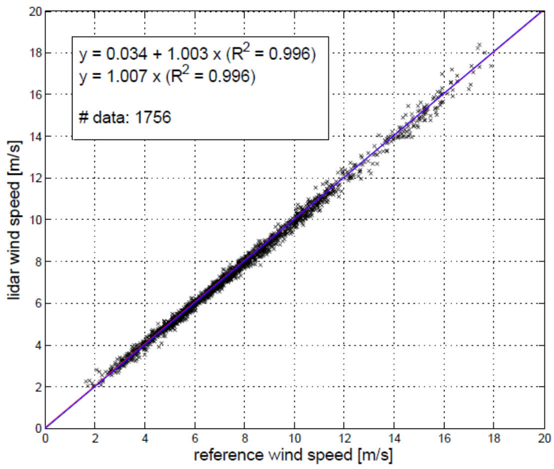
(a) See Reference [10].



(b) See Reference [15].

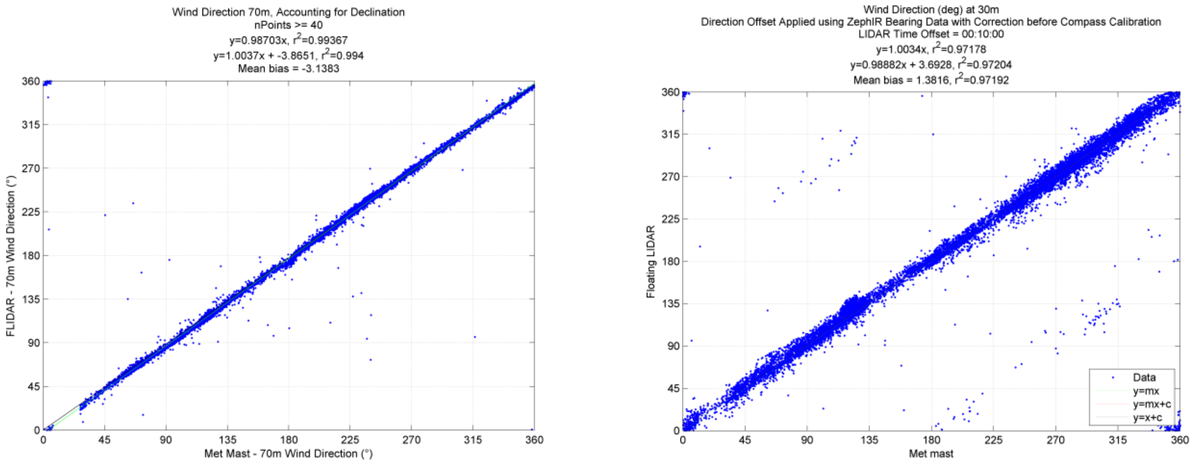


(c) See Reference [8].



(d) See Reference [11].

Figure 10: Examples of wind speed correlations from various sources.
(Note that the recommended practice is to use single-variant regression, whereas these figures also show two-variant regressions.)



(a) See Reference [10].

(b) See Reference [15].

Figure 11: Examples of wind direction correlations from various sources

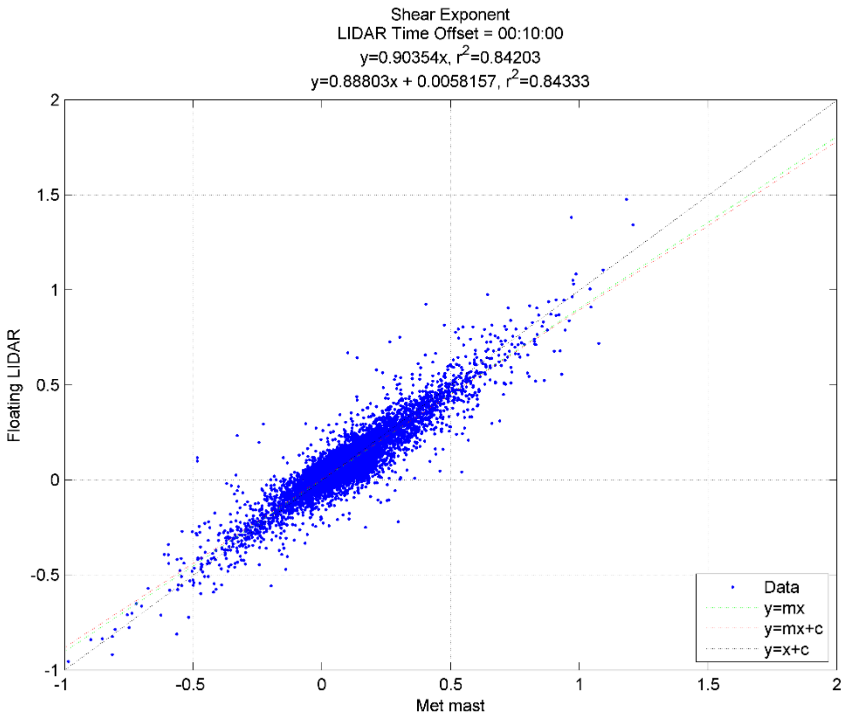
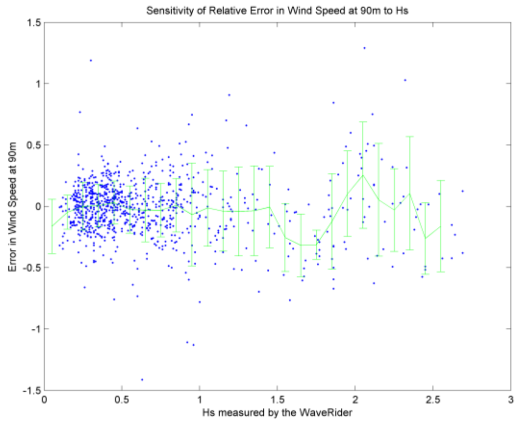
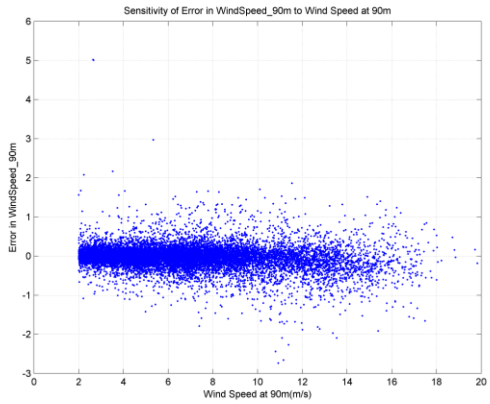


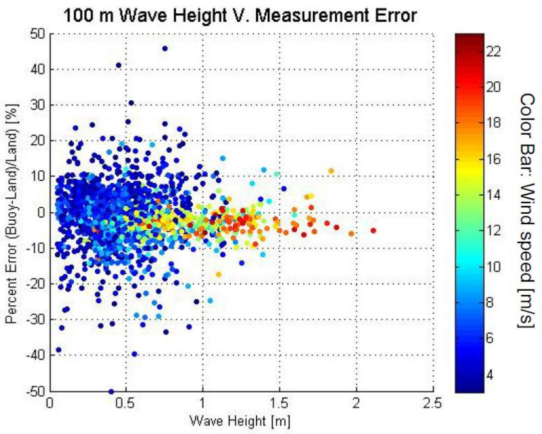
Figure 12: Example of wind shear correlation, previously unpublished but taken from the same data set as reference [15]. Reference heights of 50 m and 90 m were used. (Note that the recommended practice is to use single-variant regression, whereas these figures also show two-variant regressions.)



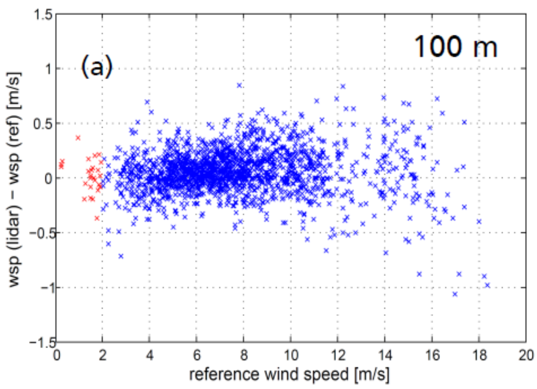
(a) Example of wind speed error sensitivity to significant wave height (Reference [10]).



(b) Example of wind speed error sensitivity to wind speed (Reference [15]).



(c) Example of wind speed error sensitivity to wave height (Reference [8]).



(d) Example of wind speed error sensitivity to wind speed (Reference [11]).

Figure 13: Examples of wind speed error sensitivity to different factors from various sources

7.3 Sensitivity of Wind Speed and Wind Direction Accuracy Results

RP 99: Sensitivity of errors in wind speed and wind direction

The error associated with each wind speed and direction data point comparison should be calculated and plotted against the parameters listed below:

- Wind speed and wind direction;
- Significant and maximum wave height;
- Peak and mean wave period;
- Wave steepness (which can be derived from wave height and period).

In addition, the sensitivity of the wind speed and direction error should also be calculated and plotted against any other parameters which were deemed to be significant in the design of the trial (see Section 5.5). Some examples are shown in Figure 13. There is no specific acceptance criterion for these sensitivity studies. It is recommended that they are reviewed by a suitably qualified and experienced analyst and their acceptability assessed on a case-by-case basis.

The sensitivity study builds the basis for a type classification test as outlined in 7.6. If such a full uncertainty assessment is performed, this RP may be ignored.

7.4 Availability

RP 100: System and data availability definitions

The following availability definitions should be used as KPIs (these are taken from the OWA Roadmap [7]):

- Monthly System Availability: One-Month Average.
  - The FLS is ready to function according to specifications and to deliver data, taking into account all time stamped data entries in the output data files including flagged data (e.g. by NaNs or 9999s) for the given month. *Note that for the system to be considered "ready", at least one valid data point must be recorded (at any height).*
  - The Monthly Overall System Availability is the number of those time stamped data entries relative to the maximum possible number of (here 10-minute) data entries including periods of maintenance within the respective month.
- Overall System Availability: Campaign Average
  - The FLS is ready to function according to specifications and to deliver data, taking into account all time stamped data entries in the output data files including flagged

data (e.g. by NaNs or 9999s) for the pre-defined total campaign length. *Note that for the system to be considered "ready", at least one valid data point must be recorded (at any height).*

- The Overall System Availability is the number of those time stamped data entries relative to the maximum possible number of (here 10 minute) data entries including periods of maintenance within the pre-defined total campaign period.

- Monthly Post-processed Data Availability: One-Month Average
    - The Monthly Post-processed Data Availability is the number of those data entries remaining
        - after system internal (unseen) filtering (e.g. -22dB CNR filter), i.e. excluding (NaN or 999) flagged data entries,
        - and after application of quality filters based on system own parameters, to be defined and applied in a post processing step on the basis of LiDAR contractor guidelines,
    - relative to the maximum possible number of (here 10-minute) data entries within the respective month, regardless of the environmental conditions within this period. Note that there should be a data availability value for each measurement height.

- Overall Post-processed Data Availability
    - The Overall Post-processed Data Availability is the number of those data entries remaining
        - after system internal (unseen) filtering (e.g. -22dB CNR filter), i.e. excluding (NaN or 999) flagged data entries,
        - and after application of quality filters based on system own parameters, to be defined and applied in a post processing step on the basis of LiDAR contractor guidelines,
    - relative to the maximum possible number of (here 10-minute) data entries within the pre-defined total campaign period regardless of the environmental conditions within this period. Note that there should be a data availability value for each measurement height.

Note that in the above, "monthly" does not imply a calendar month, rather a 30-day period.

RP 101: Other KPIs relating to availability and reliability

A number of other KPIs relating to availability and reliability should be recorded from the trial data. These are defined as follows, and are taken from the OWA Roadmap document [7]:

- *Number of Maintenance Visits.* Number of visits to the floating LiDAR system by either the supplier or an authorised third party to maintain and service the system, making a distinction between planned and unplanned activity.
- *Number of Unscheduled Outages.* Number of unscheduled outages of the floating LiDAR system in addition to scheduled service outages. Each outage needs to be documented regarding possible cause of outage, exact time / duration and action performed to overcome the unscheduled outage.
- *Uptime of Communication System.* To be documented and reported by the supplier.

7.5 Acceptance Criteria

<u>RP 102: FLS trial results acceptance criteria – accuracy</u>

Having performed an analysis of wind speed and direction accuracy according to Section 7.2, suitable acceptance thresholds for accuracy are summarised in Table 3A:

- These acceptance criteria should be applied to the wind speed and direction correlations (see Section 7.2) at all measurement heights. This is consistent with the OWA Roadmap (see reference [7) wind speed and direction criteria.
- For the wind shear parameter correlation, no specific acceptance criterion is defined. However, the wind shear parameter correlation should be examined by suitably qualified and experienced analysts and any unexpected results investigated.

<u>RP 103: FLS trial results acceptance criteria - availability</u>

Using the availability definitions from Section 7.4, suitable acceptance thresholds for availability are summarised in Table 4A – these should be applied.

7.6 Assessment of uncertainty of FLS (wind speed) measurements

The aim of this section is to outline a framework for the assessment of the uncertainty of FLS measurements. For this it follows the procedure developed for IEC 61400-12-1 Annex L [12] where a framework for the uncertainty of ground-based LiDAR profiler measurements for a power performance test is described. Future work may adapt or further develop this procedure as experience is gained in its application. The prescribed procedure, as graphically outlined in Figure 14, refers to a rather high level of detail, and may be adjusted for alternative applications (as e.g. a WRA that is in the focus of this document) or a measurement system that has not yet reached full maturity.

<u>RP 104: Assessment of uncertainty from FLS trial results.</u>

The uncertainty budget of the FLS measurements in the final application is made up of different uncertainty components as detailed in Annex L of [12]. These components are in part to be derived from the results of an FLS trial, in particular in terms of (I) a performance verification test and (II) a system classification. Note that the performance verification test should be performed on the FLS unit to be used in the final application, which may or may not be the same unit from which the system classification is derived.

Note 31: Differentiation between performance verification and system classification.

In a performance verification test, the performance of the FLS is assessed in relation to the reference measurements for the specific external conditions under the trial. In order to consider deviating conditions under the final application, the sensitivity of the trial results to selected external parameters is investigated and evaluated in terms of a system classification. The detailed procedure for this evaluation is transferred from the onshore test (as detailed in Annex L of [12]) to an offshore setup, including additional external parameters that characterize the wave conditions. The classification results allow to account for deviating and varying external conditions in the final applications by adding a corresponding uncertainty contribution. Alternatively, a corresponding uncertainty component may be estimated as a typical type B (see [16]) component based on the experience of a qualified institute.

RP 105: Assessment of uncertainty (I) resulting from FLS performance verification test.

The assessment is based on the wind speed measurements of the FLS and a reference instrument from an offshore FLS verification test that is performed prior to deployment according to the recommendations in this document (see Section 6.2).

A bin-averaging procedure should be used to compare the measurements from the FLS and the reference instrument, the bin-wise deviation between the two sets of measurements is considered the key result. As in Annex L of [12], the width and centre of the bins should be as follows: 0.5 m/s wide reference wind speed bins centred on multiple integers of 0.5 m/s. For each bin the mean value and standard deviation of the deviations should be computed.

The measurements of the FLS are linked to the following (bin-wise) systematic uncertainties resulting from the performance verification test:

a) the standard uncertainty of the reference sensor (assessed e.g. according to Annex L of [12]);
b) the mean deviation of the FLS and the reference wind speed measurements;
c) the standard uncertainty of the FLS measurement calculated as the standard deviation of the measurements divided by the square root of the number of data records per bin (category A uncertainty of verification test);
d) uncertainty of the FLS due to mounting effects during the performance verification test – if applicable.

The different uncertainty components should be assumed to be independent from each other and should be added in quadrature for each wind speed bin.

Note 32: Further components of uncertainty resulting from performance verification test.

In Annex L of [12] two further contributions are mentioned:

- uncertainty of the remote sensing device due to non-homogenous flow within the measurement volume during the performance verification test, and
- site effects as an additional uncertainty if the remote sensing device and the reference sensor are separated from each other by a significant distance.

These two contributions are not further considered here. They are assumed to be negligible for typical offshore setups (i.e. with a high degree of flow homogeneity and the FLS unit installed close to the reference, see RP 76 and RP 78) , and sites where they have a significant contribution are to be avoided.

Whether the uncertainty due to mounting effects listed under d) above should be considered, might depend on the specific type of FLS. For some types, it is assumed that the mounting may be indirectly covered by the sensitivities to the sea conditions studied as part of the system classification test.

Note 33: Use of reference LiDAR device in FLS performance verification test.

According to Note 18 in this document, the reference wind speed measurement instrument in the trial does not necessarily have to be an equipped offshore met mast but could also be e.g. an industry proven LiDAR on a fixed platform. In this case, the reference uncertainty a) above (in this case for the reference LiDAR) would be based on the results of a LiDAR verification test against an onshore met mast and a corresponding type classification of the used reference LiDAR. Although this is one more step in the chain of tracing back the uncertainty, it is possible that the final uncertainty of the FLS measurements is lower when an optimal setup is used – e.g. with an onshore met mast with optimal mast characteristics and an ideal test site, consequently as minimal as possible uncertainties for the reference LiDAR, and a very good agreement between fixed and floating LiDAR offshore. The different parts in this chain provide possibilities to minimize the final uncertainty provided that also the FLS shows a good performance.

RP 106: Assessment of uncertainty (II) resulting from FLS classification.

As part of the FLS trial, a classification test should be performed for the FLS following the procedure outlined in section L.2 in [12]. In essence this means that the observed deviations in wind speed between the measurements of the FLS and the reference sensor are related to the variations in different external environmental parameters. Corresponding sensitivity tests – one for each considered parameter, i.e. a plot of the percentage deviation between mean wind speed by FLS and reference sensor versus considered external parameter as independent variable – are evaluated in terms of a two-parameter OLS (Ordinary Least Squares) linear regression quantifying the dependency.

The following environmental variables (EVs) may be found to be relevant, as proposed in Annex L of [12]: wind shear exponent, turbulence intensity, rain, LiDAR availability, wind direction, air temperature, temperature gradient, air density, flow inclination, wind veer gradient. Furthermore, for an offshore trial under floating conditions, the sea state information should be considered: wave height, wave period, and any other identified parameter.

An accuracy class is calculated from the product of the found slope of the regression and a considered variable range, and only significant variables are considered. For details of the evaluation and calculation it is referred to Annex L of [12]. Note that the document does highlight the importance of assessing the interdependency between EVs but does not prescribe an explicit procedure for doing this.

The category B uncertainty of the wind speed measurement due to the influence of EVs on the performance of the FLS uses the results of this classification and is described in Section 8.6. A graphical representation of how this is evaluated is included in Figure 14.

<u>Note 34: Expanding Representative Sea States beyond the trial envelope</u>

As noted in RP 117, the range of environmental parameters experienced and whether certain limits should be applied needs consideration. One potential route to ascertaining appropriate uncertainty estimates for data gathered in sea states outside the range of those experienced in trials may be to apply a sea-keeping model. For FLS application this approach is considered to be of interest but not yet mature enough to make specific recommendations. Further information is included in Appendix C.

<u>Note 35: Number of trials needed for complete FLS type classification.</u>

Whereas a pre-deployment performance verification test should be performed for each individual FLS unit and is based on exactly one trial, a type classification according to Annex L of [12] is to be performed for a minimum of two devices of a specific type of remote sensing device at a minimum of two different sites for a sufficiently long period covering a sufficiently significant range for each relevant environmental variable. For an FLS this approach is seen to be related to a comparatively high effort and high costs. Nevertheless it is recommendable to base the insight in terms of observed sensitivities on the results from more than one trial and different sites with different ranges of external conditions or different seasons. Such a deeper insight with respect to the FLS performance may be related to a higher stage of maturity of the FLS. The other way round, a full FLS type classification with similar requirements as in Annex L of [12] may be a prerequisite for an FLS type to reach the Roadmap stage 3 status "commercial".

7.7 Lessons Learnt

<u>RP 107: Capturing and disseminating lessons learnt.</u>

The opportunity to learn from experience during a FLS deployment is considerable. It is recommended that there is a formal "lessons learnt" activity involving all stakeholders on completion of the campaign. The scope of the activity should include all aspects including planning, procurement, deployment, maintenance (including all failures or outages), recovery as well as system accuracy and reliability. Where possible and acknowledging commercial sensitivities, details of lessons learnt should be disseminated to the offshore wind industry in general.

8 Wind Resource Assessment

Section 6 describes recommended practices for using a FLS for wind resource assessment purposes. Having carried out measurements in this way, the question arises as to how to best assess and use the results. This section describes the required data processing and comparisons and also relevant compliance and acceptance thresholds.

Note that this section is not prescriptive on how to use FLS wind data in a wind resource assessment, rather provides guidance on methods to assess the data quality using a FLS. See Section 1.5 for more information on limitations of the recommended practice.

8.1 Independence of results analysis

RP 108: Independence of pre-deployment checks and results analysis

Any pre-deployment verification of the LiDAR unit or the FLS system (see Section 5.2) should be reviewed by a suitably skilled and experienced organisation independent from the FLS OEM in order for the campaign outcomes to be credible. This should include verification of the correct execution of the pre-deployment verification design.

8.2 Wind Speed and Direction Accuracy

RP 109: Wind speed and direction correlations: pre-deployment verification

The wind speed and direction accuracy of the FLS during the pre-deployment check should be assessed as described for a dedicated FLS trial in Section 7.2 (if a pre-deployment FLS Verification Test has been carried out).

RP 110: KPIs for wind speed and direction accuracy: pre-deployment verification

The applicable KPIs are those described in Section 7.2.

RP 111: Wind speed and direction functionality checks at wind resource assessment site

It is assumed that at the wind resource assessment site there is no nearby high quality reference wind speed or direction measurement system available. A functionality check using other available sources of data should be carried out on the wind speed and direction data capture, as would be the case for any other primary measurement system used in wind resource assessment. The nature of such functionality checks is an established element of the wind resource assessment discipline and not in the scope of this document.

8.3 Sensitivity of Wind Speed and Direction Accuracy Results

RP 112: Sensitivity of wind speed and direction error: pre-deployment verification

The sensitivity of wind speed and direction accuracy of the FLS during the pre-deployment verification should be assessed as described for a dedicated FLS trial in Section 7.3.

8.4 Availability

RP 113: System and data availability definitions

The KPIs defined for a full-scale trial (see Section 7.4) should be used, for both the pre-deployment verification phase and the wind resource assessment phase.

RP 114: Other KPIs relating to availability and reliability

KPIs for Number of Maintenance Visits, Number of Unscheduled Outages, Uptime of Communication System defined for a full-scale trial (see Section 7.4) should be used, for both the pre-deployment verification phase and the wind resource assessment phase.

8.5 Acceptance Criteria

RP 115: Pre-deployment verification acceptance criteria – accuracy

Suitable acceptance thresholds for accuracy are summarised in Table 3A. These are applicable to the pre-deployment verification phase for the FLS. These thresholds should not be interpreted as binary pass/fail criteria, but should be interpreted by suitably qualified and experienced analysts.

RP 116: Pre-deployment verification and wind resource assessment acceptance criteria - availability

Suitable acceptance thresholds for availability are summarised in Table 4A. These are applicable to the pre-deployment verification phase for the FLS. For the wind resource acceptance phase, these are a useful guide to expected performance. These thresholds should not be interpreted as binary pass/fail criteria, but should be interpreted by suitably qualified and experienced analysts.

8.6 Assessment of uncertainty of FLS measurements

RP 117: Use of observed sensitivities in final application.

The category B uncertainty of the wind speed measurement due to the influence of EVs on the performance of the FLS should take into account the deviations of the mean values of the EVs during the performance verification test and the final application (e.g. the WRA assessment); the corresponding calculation is detailed in L.4.3 of [12].

As the uncertainty resulting from an FLS classification and the sensitivities observed therein are calculated from the derived regression slopes and for a range of the considered EVs, these ranges – or their mean values, respectively – should either be predicted in advance or monitored during the final application, e.g. at the actual offshore windfarm project site. The latter is recommended in order to reduce the related uncertainty.

For the monitoring of the external conditions, it should be assured that all environmental variables found to be significant in the FLS classification are measured during the application either with a sensor that is part of the FLS itself or with an additional measurement system close-by.

An alternative outcome of a sensitivity test might be that the performance of an FLS is not acceptable anymore for a certain range of conditions or associated with a higher uncertainty. Corresponding limits for certain environmental variables should be identified and considered for the evaluation of the final measurements, either for filtering out corresponding wind speed data or for assigning them with a higher uncertainty. The data basis for the identification of these limits should be as long and significant (in terms of covering the relevant conditions) as possible.

RP 118: Estimation of final uncertainty budget for FLS.

The following components should be taken into account for the evaluation of the uncertainty of the final FLS measurements:

a) uncertainty resulting from the FLS performance verification test as outlined in RP 105 (I);
b) uncertainty resulting from the classification of the FLS as outlined in RP 106 (II) and in RP 117;
c) uncertainty due to mounting effects of the FLS or the LiDAR device within the FLS – if not covered by sensitivities found for classification test.

Hereby, it is assumed that the flow within the measurement volume of the FLS is sufficiently homogenous and there is no significant variation in the flow across the site of interest. If these assumptions do not hold, additional uncertainty components should be considered.

Figure 14 summarizes the complete procedure outlined in this section for assessing the uncertainty of FLS (wind speed) measurements.

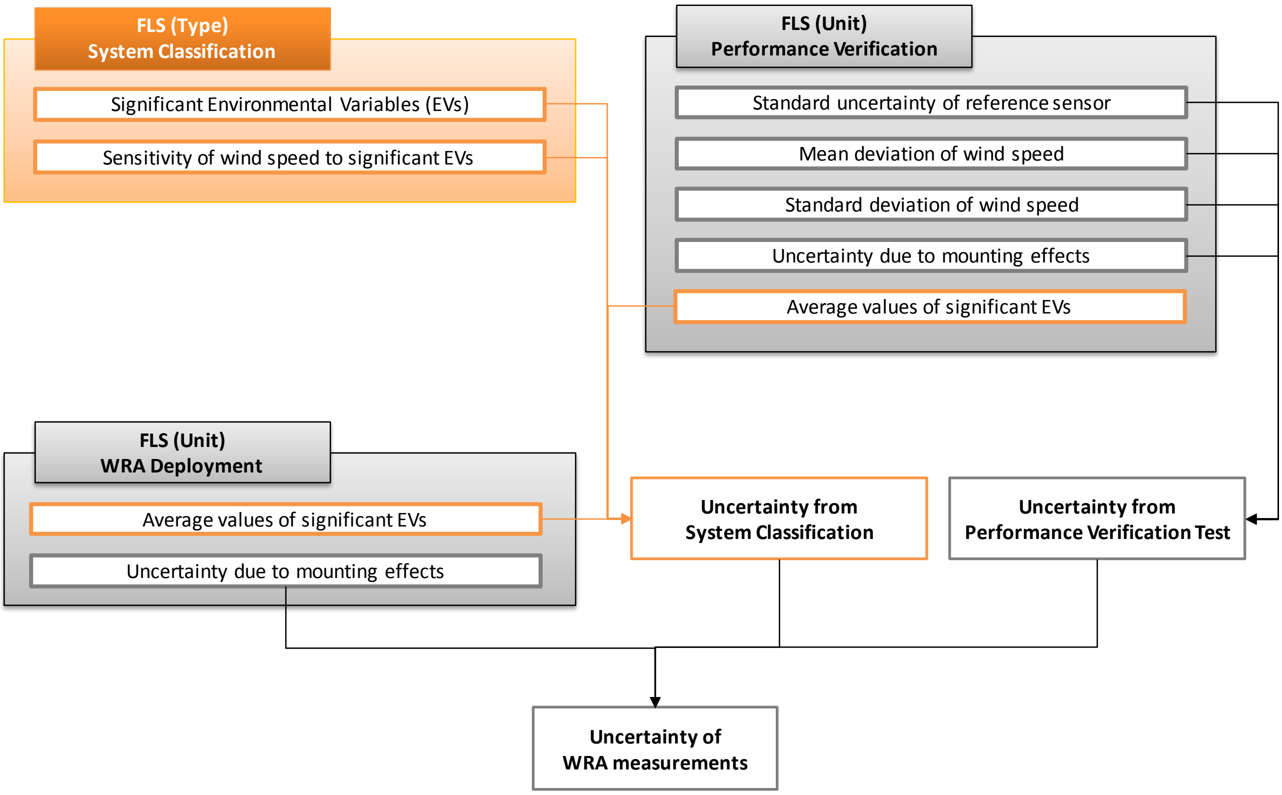


Figure 14: Flow chart summarizing the procedure for assessing the uncertainty of FLS (wind speed) measurements.

8.7 Lessons Learnt

<u>RP 119: Capturing and disseminating lessons learnt.</u>

As for RP 107.

9 Recommendations for further work

In the course of developing this recommended practice document the authors are aware that this is a "stepping-stone" on the way to a normative standard. As is natural in such a case, a number of areas have been identified where the industry would benefit from further work on developing or codifying recommended practice. These are summarised as follows:

1. **Case Study.** Illustration of all of the points in this document, and in future developments of this document, through a record of how each element was tackled for a real case study, would be very informative. This particularly applies to data uncertainty topics.

2. **Understanding gust and turbulence**. What value can be derived from gust and turbulence measurements from floating LiDAR systems?

3. **Development of a repository of floating LiDAR system applications.**

4. **Re-assess the OWA Roadmap acceptance criteria.** As the body of FLS trial data has grown significantly since the Roadmap was first introduced, it would be worthwhile to review the Roadmap criteria in the light of this data.

5. **Use of hydrodynamics model.** At present it is not clear how a hydrodynamics model can be used to extend the use of FLS to conditions not experienced in trials. This should be investigated further.

Most of the above items are considered to be achievable without further early-stage research, with the probable exception of item 2. It is the authors' recommendation that these areas, and any others prioritised by industry stakeholders, are included in a future iteration of this document.

Other subject matter areas which are also of relevance to FLS deployments, and the authors do not believe are comprehensively covered here are installation, licensing and safety. However, this work has involved extensive stakeholder engagement and in that process there has been no call for further work on these topics, hence they are not currently recommended for further development.

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Appendix A: Summary of Performance Evaluation Criteria

This Appendix summarises criteria used to indicate or assess FLS maturity and/or performance. These criteria are referred to from the main body of the document.

Stage	Description
1. Baseline	As a pre-requisite, the LiDAR measurement unit itself should have achieved wide-spread acceptance within the onshore wind industry as "proven" in the field of wind resource characterisation for non-complex terrain sites at least.
2. Pre-Commercial	Following a successful pilot validation trial, the floating LiDAR technology may be utilised commercially in limited circumstances - specifically in conditions similar to those experienced during the trial. Elevated measurement uncertainty assumptions may be expected for such application, when benchmarked against the deployment of a conventional fixed offshore meteorological mast.
3. Commercial	Following successful further trials and early commercial deployments covering a range of site conditions, a sufficient body of evidence is accumulated to relax the elevated uncertainty assumptions.

Table 1A: Description of OWA Roadmap [7] maturity stages for floating LiDAR systems.

Definition	Acceptance Criteria across total of six (6) months data
Monthly System Availability – 1 Month Average	⩾90%
Overall System Availability – Campaign Average	⩾95%
Monthly Post-processed Data Availability – 1 Month Average	⩾80%
Overall Post-processed Data Availability	⩾85%

Table 2A: Availability/reliability Criteria from OWA Roadmap [7]. Note that availability metric definitions are described in Section 7.4.

Definition	Acceptance Criterion	
	Best Practice	Minimum
Mean Wind Speed – Slope [single variant regression]	0.98 – 1.02	0.97 – 1.03
Mean Wind Speed – Coefficient of Determination ("R-squared") [single variant regression]	> 0.98	> 0.97
Mean Wind Direction – Slope [two variant regression]	0.97 – 1.03	0.95 – 1.05
Mean Wind Direction – Offset (absolute value). [two variant regression]	< 5°	< 10°
Mean Wind Direction – Coefficient of Determination ("R-squared") [two variant regression]	> 0.97	> 0.95

Table 3A: Wind speed and direction accuracy criteria from OWA Roadmap [7]. Note that applicable data ranges and availabilities are described in Section 7.2.

Recommended Minimum Requirements	Trial	Purpose	
		WRA (greater uncertainty)	WRA (lower uncertainty)
OWA Roadmap Maturity Level (see Table 1A)	Baseline	Pre-commercial	Commercial
Availability (Table 2A)	Design is fit for purpose to meet criteria	Criteria have been met in at least one trial	Criteria have been met in several independent trials
Accuracy (see Table 3A)	Evidence that LiDAR type can achieve criteria in a static test Design of motion compensation or limitation is fit for purpose to meet criteria	Criteria have been met in at least one trial	Criteria have been met in several independent trials

Table 4A: Summary of approach for wind speed and direction suitability assessment, relating to OWA Roadmap [7] assessment criteria.

Appendix B: Planning and Permitting

This section makes some general comments which should be useful for owner/operators engaging with the statutory licensing, planning and/or permitting authorities. Although a few specific notes are made, they are generic in nature because the engagement required, and the authorities involved, vary significantly between jurisdictions.

1B Using this Section

For those planning to use a FLS for wind resource assessment, or planning to trial a FLS for that purpose, this section is useful for aiding their understanding of the FLS permitting context, and planning activity and timescales accordingly.

2B Notes and Recommendations related to Permitting

<u>Note 36: Licensing – general.</u>

Experience has shown that, for both suppliers and for owner/operators, the initial expectations of timescales to obtain the necessary consents can easily be underestimated. Consenting timescales can be the pacing item for floating LiDAR deployments, with a 16-week period being seen as realistic based on UK waters, and 8 weeks perhaps typical in German waters. It is not clear how this varies with different types of FLS, e.g. marine buoys versus spar buoys. Some additional observations are as follows:

- For a FLS trial, where it is required to locate the FLS close to a met mast, it can be quicker to deploy the FLS within the mast operator's area of responsibility (close to the mast) compared to outside this area.

- Current and prior usage of the proposed mast location can have a strong bearing on the timescale required for consenting.

<u>RP 120: Engagement with authorities.</u>

It is recommended to become aware of and consult with the relevant authorities as early as possible in the process, and if possible engage in an active dialogue to reduce the risk of delay.

<u>Note 37: Licensing – vessel classification.</u>

The FLS may not conform neatly with existing vessel classifications used by licensing authorities. The manner in which the buoy or floating platform is described in the consenting application can complicate the approval, and making progress on this topic can be expedited by actively seeking individuals with prior experience and/or an active dialogue with the licensing authorities.

Note 38: Specific learning points from a UK waters deployment in the Irish Sea

The following requirements for making a FLS marine license application (note in UK waters) have been provided by RWE following an FLS trial (see [10]) carried out in the Irish Sea:

- Description of the FLS to be used, including photograph of the device
- Schematic diagrams of the FLS and the mooring system
- Duration of the project (start/end date)
- Location of the FLS - Lat/Long - degree and decimal minutes. (e.g. 3° 30.48'W 53° 28.78'N)
- Contractor details
- Full details of the proposed project, including the method of construction
- Justification for its requirement on the project
- Area influence of the FLS (i.e. area within which it can drift with the proposed mooring system)
- Detailed method of construction, and measures to be taken, to minimise any risk to the marine environment, prevent undue interference to others, mooring of barges, pontoons, transhipment vessels, maintain navigational safety, including marking and lighting of works.
- Height of the highest point on the buoy above the water surface.
- Dimensions of the mooring to cover the seabed, and tonnage.
- Details of the power generation and power storage equipment on the buoy.
- Frequency of potential servicing and refuelling activities.
- Description of the mooring system
- Mooring material datasheet - including source of material.
- Description of how the FLS will be deployed (timescales and vessel if known). Vessel specification document (can be provided at a later stage if unknown)
- Deployment method statement (pictures of deployment method, if available)
- Vessel route plan - description of the method of delivery.
- Decommissioning plan

- Map 1 - scaled to 1:25,000 of larger, admiralty chart, mean high water spring mark, FLS location, project area/lease boundary, other constraints (other users of the sea, for example; navigation, dredging licences etc), environmental sensitive areas (SPA, SAC, SSSI, RAMSAR, NNR, LNR, Areas of outstanding natural beauty).
- Map 2 - schematic drawing on a location plan (1:2,500 to 1:10,000, A4 or A3) showing the full extent of the project in relation to the surrounding area.
- Reporting on benthic environment from the project - technical report produced for the EIA, or pre-construction benthic survey work (consents team should already have this)
- Stakeholder discussions
    - Trinity House Lighthouse Service and the Maritime and Coastguard Agency, with regards to safe navigation lightings and markings.
    - The Crown Estate agreement
    - Public notices of the consent application are required - identify two locations in the vicinity of the project/or port (e.g. library/museum/arts centre).

Appendix C: Wind Shear KPI

In this Appendix the requirement for a wind shear KPI and associated acceptance threshold is discussed. The evidence base for performing shear comparisons is not strong enough to define acceptance thresholds at present. The evidence base that may be developed in order to achieve this in future is discussed.

Note 39: The requirement for a wind shear KPI

In the OWA Roadmap [7], it is recommended to compare the shear from FLS measurements with the shear from the trusted reference source measurements. This recommendation is also made in this document, see RP 95, RP 96, RP 97, RP 98 and RP 102. The OWA Roadmap does not provide an acceptance threshold for the quality of agreement, nor is one proposed here. It would be useful to have such an acceptance threshold, and it is useful to explain the reasoning behind this. First of all, shear is important for the following two reasons:

- Hub-height wind speed is central to WRA. If only a shorter mast is available, it is normal to extrapolate wind speed up to hub height as part of the WRA.
- The emerging Rotor-Equivalent Wind Speed (REWS) approach for power curves puts a new focus on shear which is expected to become increasingly influential and likely to migrate into WRA methodologies.

This gives rise to the following reasons why shear is important when employing FLS in a WRA context:

- Wind speed measurements at heights higher than hub height will readily be obtained using a FLS. This may appear to negate the requirement to extrapolate wind speeds to higher heights than those measured conventionally. However, the FLS wind speed measurements at those higher heights are unlikely to have been directly validated. It is anticipated that a WRA analyst would indeed employ these measurements, but due to lower confidence (than for validated lower heights), the analyst is also very likely to extrapolate from validated FLS heights up to the higher heights as a sanity check.
- FLS (and even static or ground-based LiDARs) are not perceived as having the maturity of other measurement systems for WRA or other purposes. Adding shear to wind speed and direction KPIs would help promote acceptance and recognition of maturity i.e. by potentially demonstrating that a FLS can capture shear as well as a met mast.

Note 40: Approach to formulating a Wind Shear KPI

An example of an ordinary least squares regression of shear exponent is shown in Figure 12. Inspection of the figure highlights a challenge in defining an acceptance criterion: shear exponent is not as tangible a parameter as wind speed, therefore how to define acceptance criteria for the quality of this agreement is not at all clear. It is possible that as more such analyses are performed that an appropriate acceptance criterion will emerge for shear component agreement. However, it is also possible that the intangible nature of the shear exponent regression analysis will cause a quantified acceptance threshold to remain elusive. For this reason an alternative approach is proposed here which puts shear error in a wind speed context:

- Even if wind speed KPI acceptance criteria are met (at the measurement heights from which shear is calculated), it is possible for a differential bias to introduce an error in the estimated shear profile. Such an error in the shear profile could result in a relatively large error in extrapolated wind speed at higher heights, as illustrated in Figure C1.
- The requirement for a shear KPI can therefore be cast as a requirement for an extrapolated wind speed KPI, as this would reveal an unacceptable differential bias.
- An appropriate acceptance threshold for the agreement of extrapolated wind speeds is considered to be the existing "slope" criterion for wind speed agreement.
- An extrapolation distance of 40 m above the uppermost direct measurement level is considered to be representative of typical extrapolation requirements.

As a result, a relatively simple wind shear KPI is proposed, the procedure for which can be summarised as:

- Calculate shear exponent for both trusted reference measurement system and FLS, ideally separated by about 40 m, where one of the two measurement heights is the highest available;
- Use the shear exponent to extrapolate vertically by a further 40 m;
- Calculate a linear regression for the extrapolated wind speeds;
- For this correlation, the "Mean Wind Speed – Slope" criterion from Table 3A should be applied:
  - Exceeding the acceptance criterion indicates an unacceptable differential bias in wind speed measurement at different heights which should be investigated;
  - Achieving the acceptance criterion provides a good indication that the FLS is capturing shear as well as the trusted reference system (e.g. met mast).
  - Note that the "Mean Wind Speed - Coefficient of Determination" criterion should not be applied.

During the course of this work, two trial data sets for different FLS systems were analysed in this way. Following the above procedure the wind speed acceptance criterion for slope was achieved, and was indeed still achieved for extrapolations of greater than 100m. On their own these observations support a view that the above procedure is not unduly strict. A wider analysis and evidence base would be required before the procedure would be accepted as recommended practice.

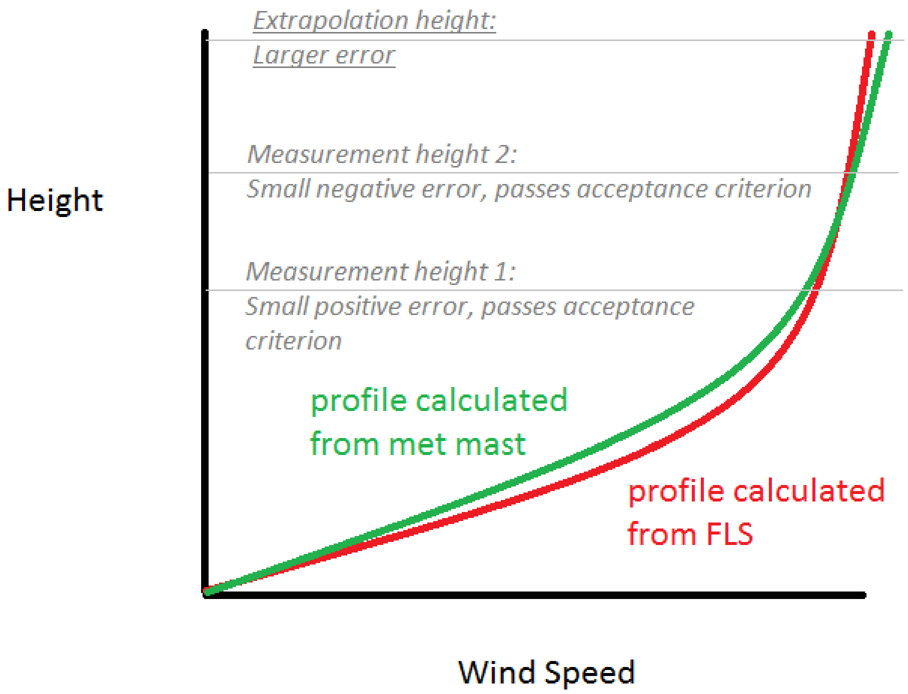

Figure C1: Potential for differential bias in wind speed measurement resulting in relatively large error in extrapolated wind speed.

Appendix D: Expanding Representative Sea States beyond the Trial Envelope

An approach which could be undertaken is to assess the motion of the buoy during the trial and use this to calibrate a "seakeeping" model of the FLS. This could then be used to establish a measurement model for the FLS alongside a calibrated sea state model. An example of how the various influence quantities could be incorporated is provided below.

The diagram shows the uncontrolled influence factors on the left – these are not exhaustive. Above and below the Hydrodynamic Function are the factors which are controlled through the knowledge of the site (i.e. they are variables which are known at the time of deployment). Any correction scheme for motion compensation is included, along with a model of wear or other degrading factors.

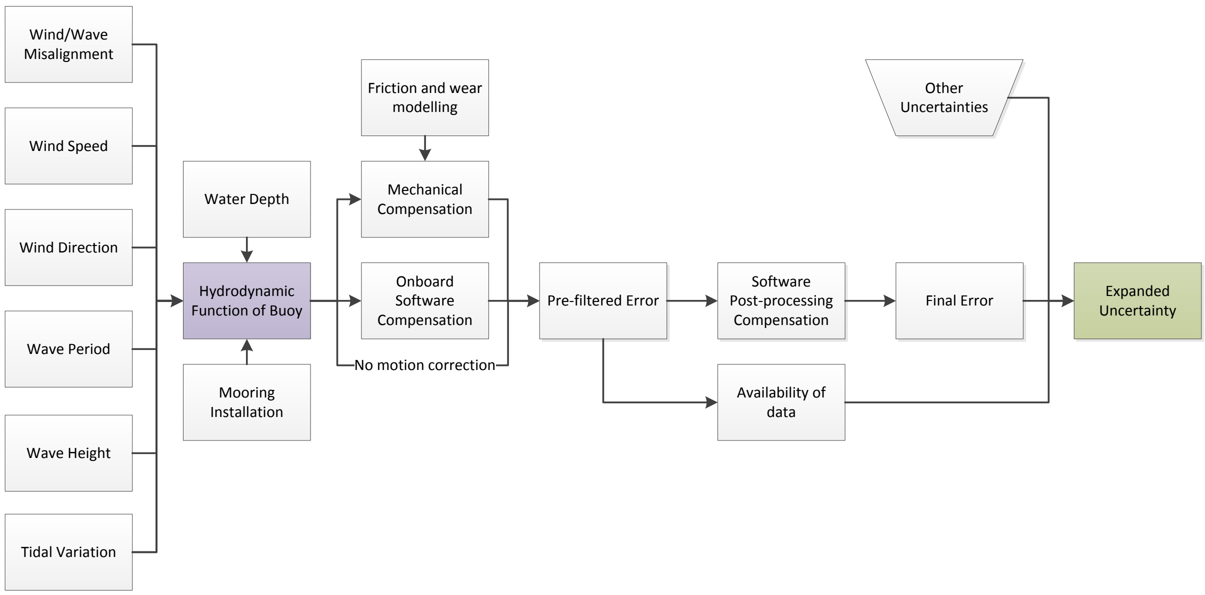

Figure D1: Schematic Representation of Sea-Keeping Model

Sea-keeping models are common in the ship-building and floating offshore structure community (such as spar buoys for oil and gas), as are the data input requirements needed to calibrate these models. The models can ultimately allow for establishing sub-ranges of sea states which will aid in determining uncertainty:

- The range of sea states for which the FLS is already validated (already known without the model);
- The range of sea states outside the validated range, for which the buoy motion range lies within the envelope experienced in the validated range;
- The range of sea states outside the validated range, for which the LiDAR motion range (i.e. the demands on the motion compensation system) lies within the envelope experienced in the validated range;
- The range of sea states for which there is no support from prior FLS validation.

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